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SURVEY OF THE POSSIBILITY OF SHORT-RANGE RADIO PREDICTIONS FROM METEOROLOGICAL DATA

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Institute for Telecommunication Sciences
Boulder, Colorado

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RESEARCH LABORATORIES
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SURVEY OF THE POSSIBILITY OF SHORT-RANGE RADIO PREDICTIONS FROM METEOROLOGICAL DATA

L. P. Riggs
C. A. Samson

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Table of Contents

Table of Contents (Continued)

A Survey of the Possibility of Short-Range Radio Predictions from Meteorological Data

by

L. P. Riggs and C. A. Samson

The results of a literature survey of weather-related effects on tropospheric radio propagation are summarized and presented in tabular form. Consideration of the available weather data, the prediction probability for various weather factors, and the limited knowledge of radio-weather relationships, leads to the conclusion that only very limited propagation predictions based on weather data are possible at present.

1.0 Introduction

Tropospheric radio propagation may be affected by weather phenomena through the processes of absorption, diffraction, reflection, scattering, and refraction. One of the most important of these processes is the refraction resulting from stratifications of temperature and humidity in the lower layers of the atmosphere. Depending upon relationships with other factors, such as antenna height and topography, the changes in the radio refractivity resulting from these stratifications may improve or degrade microwave communications. Some statistical data on ducting, trapping, subrefraction, and superrefraction are already available (e.g., Bean et al., 1966), however more detailed information is needed on the specific meteorological circumstances that result in the short-period variations observed in radio propagation. In particular, it would be useful if weather forecasting techniques could be applied to the prediction of periods of anomalous propagation.

Since a thorough understanding of the relationship between radio propagation and weather phenomena is a prerequisite for short-term propagation forecasts, an extensive search of the literature was made to determine the current state of knowledge in this field.

In table 1, pages 75 to 83, the reported radio-meteoroligical relationships are summarized by categories (e.g., air masses, fog, pressure systems, and fronts). The table also lists the radio frequency used, the path length involved, the country or geographic region where the research was performed, and the page in the text where additional details may be found.

Any system of propagation forecasting based on weather data will be heavily dependent on the quality of its weather forecasts, i.e., the <u>weather</u> in a particular area or along a particular circuit must first be predicted, then the effect of the forecast weather on each radio circuit must be calculated. In section 8 of this report the problems involved in detailed short-range weather forecasting are considered, as well as the probable accuracy of forecasts for various time intervals. Estimates have also been made of the feasibility of certain types of radio-meteorological predictions using currently available data and forecast techniques. Definitions of a large number of meteorological terms are contained in section 13.

2.0 The Radio Refractive Index

The radio refractive index is defined as the ratio of the speed of propagation of a radio wave in a vacuum to the speed in a specified medium. At standard conditions of pressure and temperature near the earth's surface, the radio refractive index, n, has a value of approximately 1.0003. When evaluating refraction effects, it is generally more convenient to use a scaled-up value, N, called refractivity, which may be obtained through use of the formula:

$$N = (n-1)\,10^6 = \frac{77.6}{T}\left[P + \frac{4810\, e_s\, RH}{T}\right]$$

where P = observed pressure in millibars

T = observed temperature in degrees Kelvin

e_s = saturation vapor pressure in millibars

RH = relative humidity in percent

The Smith-Weintraub constants (1953) give an overall accuracy of $\pm$ 0.5 percent for N up to frequencies of about 30 GHz.

When normal vertical distributions of temperature and humidity prevail in the lower atmosphere, the refractive index gradient is about -40 N-units/km, and horizontally directed radio waves will have a downward curvature about one quarter of that of the earth. When the temperature profile shows an increase with height or the humidity profile shows a decrease with height, or both conditions occur simultaneously, the refractive gradient may reach the superrefractive value ($dN/dh \leq -100$ N-units/km), or the critical "ducting" intensity ($dN/dh \leq -157$ N-units/km). Ducts near the earth's surface tend to bend radio energy along the earth's contour (smooth), and very high field strengths may be recorded well beyond the normal radio horizon. If the relative humidity increases with height, or if there is an excessive temperature lapse rate, or if both occur simultaneously, a positive or subrefractive gradient may form ($dN/dh \geq 0$ N-units/km). Under these conditions the radio rays will bend upward.

Bean (1954) studied refractivity profiles for two radiosonde stations within 160 km of a 112-km path in Colorado. Over about a 2-mo. period, the presence of ducting gradients at these stations was found to coincide with the occurrences of fadeouts more than 75 percent of the time (1046 MHz transmissions, one terminal 1100 m above the other).

The most persistent and strongest refractivity gradients are those found in the vertical (Moreland, 1965), and the strongest and most persistent contribution to the decrease in refractivity with height is the decrease in pressure, which amounts to about 35 mb in the first 300 m above sea level. In the horizontal plane, such a pressure change would normally occur over a distance of several hundred kilometers, even in the vicinity of a deep low pressure system. The vertical changes of temperature and humidity are also normally more pronounced than those in the horizontal.[1] Therefore, we are concerned in the vast majority of cases only with the vertical gradients of refractivity, and since the change of pressure with height is relatively constant, the variations of temperature and humidity in the vertical are of primary importance in studies of the variation of the refractive index.

Based on the equation $\Delta N = \Delta n \times 10^6 = 0.3\ \Delta p + 5\ \Delta e - 1\ \Delta T$ (where p = barometric pressure, e = pressure of water vapor, T = temperature) Lane (1965) states that the constants in this equation, derived from a height of 1 km, do not appreciably change with height between 0 and 3 km; he therefore concludes that any change in refractive index exceeding about 10 N-units in this region must be caused mainly by a change in humidity. Durst (1946) gave the critical value of the specific humidity change necessary for ducting as 0.5 g/kg/30 m, and Bean and McGavin (1965) have shown that the turbulent fluxes of the radio refractive index and the absolute humidity are linearly related.

Other references also indicate that humidity variations are of greater importance than temperature changes in affecting the refractivity

[1] When "humidity" is used, unless otherwise specified, relative humidity is assumed, i.e., the ratio of the actual vapor pressure to the saturation vapor pressure at a given temperature. Absolute humidity refers to the mass of water vapor per unit volume of air; the mixing ratio is the mass of water vapor per unit mass of dry air; specific humidity is the mass of water vapor per unit mass of moist air. The difference between specific humidity and mixing ratio is very small and in practical applications they are used interchangeably.

at lower levels in the middle and low latitudes, although the vertical temperature variations are primarily responsible for the degree of stability in the lower atmosphere. However, in the most northerly latitudes the surface temperature inversions are the most important factor in the formation of strong refractivity gradients.

With regard to the variation of humidity with change in refractivity, Wickerts (1964) has observed that in areas where the ambient humidity is high, the variation in refractivity is generally low. When the ambient humidity is low, refractivity variations are apt to be large. Wickerts further states that, in moist air, large humidity variations are apt to occur (a) by advection of drier air; (b) in subsidence inversions, and (c) in heavy downdrafts near cumulonimbus clouds. In the case of dry air, large variations in humidity generally occur (a) by advection of moist air, (b) by convection, and (c) by subsidence inversions. Large changes in the relative humidity may also be observed in the early morning as solar heating starts to dissipate any moist surface layers that may have formed during the night.

3.0 Atmospheric Processes Influencing Refraction

A refractive gradient is the result of a temperature inversion, a humidity lapse, or a combination of both. Modifications of existing temperature and humidity profiles (and refractive gradients) are related to the processes of radiation, turbulence and convection, advection, and subsidence.

3.1 Radiation

Over land surfaces the large diurnal change in solar and terrestrial radiation is reflected in the diurnal refractive conditions. During the daytime, standard propagation conditions, and possible sub-refractive surface layers, can be found in the lower atmosphere, especially near the time of maximum heating. A clear sky at night with light winds results in a large radiative heat loss from the surface of the earth, and a surface or slightly elevated superrefractive layer may be found at the time of maximum cooling, generally at sunrise. This nocturnal inversion may extend as high as 300 m and the associated refractive gradient may be strong enough to cause ducting. This process is not a significant factor in the formation of strong refractive gradients over the ocean because there are no large diurnal variations in temperature over large water areas.

3.2 Turbulence and Convection

Convection is a principal means of energy transfer. As used in meteorology it describes atmospheric motions that are predominantly vertical. During daylight hours strong insolation may create a superadiabatic lapse rate just off the ground, especially at the time of maximum heating, that may form a subrefractive layer as thick as 700 m. Moisture is transported upwards by convective turbulence, tending to form a uniform mixing ratio in the turbulent layers. With very intense convection, the vapor pressure may even increase with height, to form what has been termed a "mixing ratio inversion" (Thayer, private communication, 1967). Refractive profiles associated with daytime heating range from standard to subrefractive depending on the solar intensity. The general shape of the profiles can be estimated by considering the air mass type, the nature of the land surface, the anticipated cloud cover, and the wind velocity. Generally speaking, the greater the degree of turbulence, the closer the actual refractive conditions will approximate standard profiles.

3.3 Advection

Advection is effective in duct formation, with the most common case being that of warm, dry air moving from land over the cold waters of the oceans. Evaporation plays an important part in this process by raising the humidity value in the layers just above the water, and the accompanying temperature inversion serves to limit the vertical diffusion of water vapor. Advection-formed ducts are usually quite shallow and are sometimes referred to as "evaporation ducts." Advection may cause similar refractive effects over land, e.g., dry warm air moving over a cold ground surface can form a duct similar to those found over the oceans, if the ground surface is moist. In general, however, conditions for advective ducts do not exist as frequently over land as over the oceans. Jeske (1964) observed that in the coastal areas of Germany advection-formed ducts cause high field strengths. He also found that evaporation ducts exceeding 19 m in thickness occurred only 1 percent of the time during a test period in 1962.

Jenkinson (1966) found that in the Bass Strait area of southern Australia fading occurred more frequently with off-shore (northerly) winds than with winds from the ocean. The fading was due to superrefractive conditions caused by advection (warm continental air moving out over the cool water). Seasonally, there was considerably less fading in the winter than in the summer. Jenkinson found one especially serious type of fading which he called the "depressed median" type. It generally occurred for a period of several hours in October of each year. For periods exceeding an hour, the median signal level would drop as much as 20 dB below its normal level, with a deeper, rapid type of fading. Two explanations were offered to account for this phenomenon: (a) subrefraction producing a large diffraction loss, and (b) ducting which isolated the receiver and transmitter from each other.

Wide variations in refractive gradients on nominally line-of-sight microwave paths can cause a severe form of fading sometimes referred to as "K" type fading (Ugai, 1961; Fukushima et al., 1962; Dougherty and Wilkerson, 1967). This includes both phase-interference or multipath fading and diffraction or "earth-bulge" fading and may be particularly severe on maritime paths.

3.4 Subsidence

Subsidence is the slow settling, or subsiding, of air that occurs in a high pressure system. The process is adiabatic and there is a rise in air temperature. This results in the formation of a stable layer, a temperature inversion, and a corresponding decrease in relative humidity. If this dry air, which has descended from high levels of the atmosphere, overlies a cooler moist air mass (such as those found over the oceans), an elevated superrefractive layer may be formed. The effects of subsidence are generally found above 1500 m except in subtropical areas where such effects are observed at lower levels. Subsidence ducts, especially in the trade wind regions, may extend over large areas and be quite persistent. Subsidence effects over land are usually not as extensive as those over the oceans and are not as persistent. Subsidence acts to intensify superrefractive layers and to eliminate subrefractive layers (Moreland, 1965).

4.0 Ray Bending by Refractivity Gradients

Pressure, temperature, and humidity generally decrease with height in such a manner that N also decreases with height. Under such a condition, horizontally transmitted radio waves are bent toward the earth's surface. Most of the propagation anomalies in the troposphere are caused by this bending, which is caused, in turn, by gradients of refractive index rather than by the actual value of the index. In an atmosphere where

N is constant, there is no refraction regardless of the value of N (Moreland, 1965). Also, only those radio rays which leave a transmitter at a very small angle are affected by the vertical variations of the refractive index. Both theoretically and practically it has been found that the effects of nonstandard refraction are negligible for rays that leave the transmitter at an angle with the horizontal of more than about 1.5°. When this angle is less than 1.5°, and especially if 0.5° or less, the radio rays are strongly affected by nonstandard refraction (Burrows and Attwood, 1949).

A consideration of temperature and humidity gradients would suggest that radio ducting gradients ($dN/dh < -157/km$) are generally found below 3 km, and there are indications that they are seldom found above that height. Cowan (1953) found that ducting gradients were generally observed below the first kilometer above the earth's surface. On the average, 30 percent of the total bending occurs in the first 100 m for an elevation angle of zero degrees, and 60 percent takes place in the first kilometer above the surface (Bean and Thayer, 1959).

Bean (1959) compiled a climatology of surface radio ducts occurring in the various climatic zones using radiosonde data from three representative stations: Swan Island, West Indies (tropical); Washington, D. C. (temperate); and Fairbanks, Alaska (arctic). Based on an analysis of 3 to 5 yr. of data (using February, May, August, and November), he found that the maximum observed incidence of ducts was 13 percent in the tropics, 10 percent in the arctic, and 5 percent in the temperate zone. A more recent study (Bean et al., 1966) shows as high as 85 percent ducting in the tropics in August and 55 percent ducting in Antarctica in August. The ducts are usually associated with pronounced surface temperature inversions (when the surface temperature is less than about -25°C) and a slight humidity lapse in the arctic, with radiation temperature inversions and associated humidity lapse in the temperate zone, and a slight temperature and humidity lapse in the tropics.

Swan Island shows a slight temperature decrease and humidity lapse, in contrast to Washington, D. C., and Fairbanks, Alaska, both of which show a temperature increase and humidity lapse. This seeming contradiction is explained by Bean as resulting from the strong vapor pressure lapse associated with a moderate temperature lapse when the surface temperature is about 30°C, as shown by Swan Island. The strong vapor pressure gradient apparently is caused by evaporation from the sea surface. In the humid tropical interior, similar behavior can apparently be caused by evapotranspiration from a rain forest environment.

The annual maximum of ground-based ducts for an arctic station occurs in the winter and for tropical stations is observed in the summer. The ducting gradients at Swan Island are about 90 percent due to humidity lapses, while ducting gradients at Fairbanks, Alaska (wintertime maximum), are all caused by strong temperature inversions associated with very low surface temperatures. The temperate zone ducting seems to be based on a combination of arctic and tropical ducting mechanisms, depending on the seasons. The winter ducts of the temperate zones appear to be of the dry-term arctic type, while the summertime ducts are mostly of the tropical humidity-lapse type.

Estimates of the probability of superrefractive and ducting gradients in all parts of the world may be obtained from a recently published atlas of radio refractivity (Bean et al., 1966), which is based on an expanded study of the climatic influence on radio refractivity.

5.0 Refraction Effects Related to Particular Weather Phenomena

5.1 Surface Temperature Inversions

Temperature inversions alone are seldom strong enough to produce a duct in the middle and low latitudes, although they are a most important factor in the process. In the tropics, low stratus clouds or extremely high moisture content would lessen the chances of duct formation (Bean and Dutton, 1966). In polar regions, however, temperature inversions are of the greatest importance in the formation of radio ducts.

Gough (1962) conducted tests along the Arabian Gulf using 80 MHz over a 130-km mixed land-water path. Periodic occurrences of strong inversions were observed at 0600 local time along with abnormally strong radio signals between Bahrain and Doha, Arabia. A rapid drop of about

40 dB was observed at about 0930 when the inversion layer was dispersed by the morning convection. A slow return to stratification was noticed about 1700. During September the mean diurnal difference in signal strength was about 40 dB, while in January only a small diurnal variation was observed.

Day and Trolese (1950) found that during winter in the Arizona desert nocturnal radiation could produce surface ducts strong enough to appreciably affect microwave propagation. The diurnal change varied from a negligible value at 63 MHz to as high as 50 dB at microwave frequencies. The frequencies of 25, 63, 170, 520, 1000, 3300, 9375, and 24,000 MHz were used in this series of tests.

Ikegami (1964) observed that the field strength of microwave transmissions showed a pronounced increase during periods of "mirage" occurrences, which are caused primarily by temperature changes. In Japan mirages are known to occur frequently in the coastal areas, especially in Toyama Bay from May to July. Ikegami also stated that microwave fading for line-of-sight paths tended to increase progressively from inland areas to the oceans, and that deep fadings were seen over sea and coastal areas.

Ugai et al. (1961) conducted field experiments in August 1958 and May 1959 using frequencies of 1500, 4000, 6720, and 11,000 MHz. A path between Asahi and Toyama Bay, Japan, was chosen because the meteorological conditions in this area were considered to be characteristic of areas along the Japanese Sea and, as mentioned above, because of the frequent occurrences of mirages. Moderate fading was observed in August, but the greatest fading range and frequency occurred in May. Surface ducts were frequently observed during the day in May and the usual diurnal trend was absent. Ducts 50 m or less in thickness had no particular peak of occurrence, while ducts 20 m in thickness were almost continually observed when mirages were present.

Gough (1955) made tests using 77.47 MHz and 174 MHz on about 100 paths of varying length in the tropics and the Mediterranean. The following remarks are based on his results: West African land paths (Nigeria and the Gold Coast) - many showed marked diurnal signal variations, ranging from steady daytime signals to very disturbed nocturnal signals attaining abnormally high levels and frequent periods of deep fades. Lake Victoria path - higher frequencies faded on this 82-km path. Coastal paths - these showed pronounced stratification but were free of land-type diurnal effects. West Africa coastal paths - free of diurnal variation. Fades were due to elevated ducts. Israel-Cyprus path - appreciable downward trend in signal level in the autumn; 174-MHz signals were less reliable than 77.47 MHz because of occasional loss of signal below noise level. Overwater fading ranges - the fading ranges for the Gold Coast, Malaya, and the Mediterranean were about the same. Overland fading ranges - paths in Malaya, Ceylon, and East Africa showed similar and less intense fading characteristics than those in other regions, primarily because of reduced atmospheric layering. The paths in Nigeria and the Gold Coast, however, showed marked nocturnal radiation fading almost to the same degree as that found on overwater paths.

Baynton et al. (1965a) studied the effect of surface temperatures and wind velocities on the formation of surface temperature inversions at Point Arguello, California. The radiation inversions observed at 0400 local time are most frequent in the winter when the surface winds blowing from the interior are at their peak. These offshore winds represent a land breeze. The nocturnal inversions apparently develop when the downslope drainage of air is cold enough to slide under the marine layer. The critical surface temperature for the formation of this overland inversion is about 9°C. The nocturnal inversion in this area is most frequent in winter, whereas for most continental locations the peak is in summer.

Jeske (1964), using frequencies of 160 MHz on a 61.7-km path and 600 MHz, 2 GHz, and 7 GHz on a 77.2-km path (16.5 GHz on a 77.2-km path was used less frequently) observed that propagation properties over the German Sea at these frequencies were largely determined by the persistent low-level evaporation duct present. In 80 percent of all cases a good correlation between the field strength and thickness of the duct was obtained, and scintillation-type fading was also noticed. For the normally used frequencies, the relationship was more marked the higher the frequency. Total trapping was found only for 7 GHz, and the field strength nearly reached the free space value. The 16.5-GHz frequency also would be expected to show total trapping, but it was used too infrequently for any positive conclusions to be reached. Jeske also observed that an increase in duct thickness from less than 1 m to 20 m corresponded to an increase in field strength of about 60 dB. The above correlations between field strength and duct thickness were characterized by correlation coefficients of 0.85 (7 GHz), 0.72 (2 GHz), 0.58 (600 MHz), and 0.53 (160 MHz). The correlation for 16.5 GHz was worse than the correlations for 7 GHz and 2 GHz. This is partly because the path was used too infrequently to get firm results and also because the critical thickness of the duct for this frequency was only about 8 m. Some errors in calculating this small duct thickness caused a disproportionately large scattering of points on the graph of field strength versus duct width. Then, too, Jeske noticed that this frequency showed perceptible absorption effects from rain and water vapor.

Ikegami (1959) studied the effect of radio ducts upon microwave fading on a 54.8-km path in Japan using 3892 MHz and 4020 MHz, with a 312-m tower. He observed that severe fading occurred almost every night (November 1954) because of intense diurnal variations in the temperature and humidity gradients just above the earth's surface (temperature inversion and marked humidity lapse). Large fading occurred on a horizontal path if the duct was near the height of the antenna, or if the duct was near the height of the lower terminal of an oblique path (terminal antennas were at different heights). No significant effects were noted if the ducts were higher than 100 m. Ikegami et al. (1966) also found good correlation between the day-to-day variations in fading range and the frequency of occurrence of ducts near the transmitter height.

Hay and Poaps (1959a) studied signal fadeouts using a frequency of 2 GHz over a 34-km path near Ottawa, Canada. The duration of the fadeouts varied from a few minutes to several hours, and occurred more frequently in summer than winter and more frequently at night than during the day. The fadeout was weak if the transition was from dry air below to moist air above, but the fadeout was strong if the transition was from moist air below to dry air above. This fadeout (when the signal strength decreased by more than 5 dB from the mean) accompanied a shallow transition layer in air vapor pressure through a layer thickness of about 30 m. These transitions were observed within several hundred meters of the ground and near the height of the antenna (60 m). The conditions for weak fadeouts are found at Ottawa most of the year, but the conditions for deep fadeouts are absent in colder weather. These transitions seem to depend on the vertical stability of the air, since they are generally observed at night when a high pressure system is present. They fade rapidly after the sun heats the surface.

5.2 Elevated Temperature Inversions

Jeske (1964) points out that the appreciable influence of the low-level evaporation duct can be exceeded by other meteorological processes at higher levels, such as advection- and subsidence-produced elevated temperature inversions, which bring about good propagation conditions for all wavelengths by partial trapping. In about 20 percent of the cases studied, where there was no correlation between high field strength and the low-level ducts, the higher fields could be attributed to elevated temperature inversions or advection ducts. The high fields in these cases were subject to long-period interference fading.

Crain et al. (1954) studied the occurrence of elevated refractive gradients in different sections of the United States. In southwestern Ohio in July and October persistent occurrences of elevated superrefractive layers were found at about 1200 to 2100 m. These layers showed great daily variation in amplitude and elevation, and their presence was generally indicated by a sharply defined haze layer and a stratus cloud boundary. The stronger layers were normally associated with a temperature inversion of 1 to 3°C. Elevated layers were observed with both tropical maritime and polar continental air. Tropical maritime air seemed to show a relatively uniform height variation of refractive index not noticed when polar continental air was present. Strong refractive layers were observed at the interface of the two types of air masses when tropical maritime air overlaid polar continental air (warm front conditions).

Along the east coast of the United States in November and December Crain again found persistent occurrence of elevated super-refractive layers, but they showed a considerably reduced amplitude from those observed in other test areas. This was to be expected, since the winter air masses would tend to have much less moisture content, and therefore there would be less chance of an intense moisture gradient. The strongest refractive gradient observed along the eastern seaboard was associated with a warm front. Crain also found refractive index differences of 40 to 50 N-units between isolated cumulus clouds and the ambient air. These differences may possibly be explained on the basis of the difference between the ambient air refractive index and that of vertically moving air currents which have a refractive index representative of a lower atmospheric level.

Crain noticed a persistent occurrence of strong refractive layers off the Washington coast in August and September, and off the California coast in October. The most commonly observed layers were associated with stratus cloud layers in the first few kilometers above the surface. The frequency of occurrence of these refractive gradients is greatly influenced by the absence or presence of the trade wind inversion.

In a field experiment at Los Angeles, California, Flock et al. (1960) used a frequency of 36 GHz on a line-of-sight path and observed small fading ranges (<0.5 dB) if temperature inversions were present that were appreciably higher than the antenna height of about 150 m. If the inversion layer was lower than the antenna height, or if a surface inversion was present, the fading range might reach 30 dB. The fading range was much lower during the day than during the night.

Kitchen et al. (1958) in field tests using 86 MHz and 203.5 MHz on an overwater path of about 600 km, found that because of the presence of an elevated duct the 86-MHz signal was received almost continuously out to about 600 km. As a result of a surface duct (about 900-m thick) high and steady signal levels were observed on 203.5 MHz to a distance about 200 km, but beyond this point the signals showed deep and rapid fading.

Lane and Sollum (1965) using 186 MHz and 174 MHz over distances of 140 and 300 km in England, found that subsidence and associated strong refractive layers in the height range of 300-1000 m were especially important in affecting microwave propagation. The greatest signal strengths were observed when stable layers were present in the range of 0.5 h_o to h_o (where h_c is the height of the point of intersection of horizon rays from the terminals, using 4/3 earth radius). Lane (1965) also observed changes of 20 to 25 N-units in layers of less than a few meters thickness and several tens of kilometers in horizontal extent. Large refractive gradients were found infrequently in clear air just below the more stable inversion layers and also just above the earth's surface. On rare occasions, under conditions of extensive high pressure, the strength of the refractive layers remained essentially the same for horizontal ranges of about 100 km. Lane's examination of about 100 radiosonde soundings showed a median thickness of about 100 m for strong layers, 25 percent were thinner than 40 m, and 10 percent were less than 8 m in thickness.

5.3 Land and Sea Breeze Circulations

When the pressure gradient is weak in coastal areas (oceans, seas, or large lakes) local wind circulations may develop. During the daytime, under the influence of solar radiation, the soil heats faster than the water, and the air near the surface is warmed and rises. This results in a pressure gradient that causes the relatively cool and moist air over the water to flow from sea to land. This sea breeze occurs along and generally perpendicular to the shore line, and is normally more intense where the land is barren than where it is covered with vegetation. Normally the sea breeze extends inland only a few kilometers and at most about 65 to 80 km (Landsberg, 1960).

The reverse of the sea breeze is the land breeze, which develops as the land becomes colder than the sea at night (since water retains its heat better than land). The land breeze is generally shallower and weaker than the sea breeze. Land and sea breezes are best developed during the dry season, with clear skies, light gradient wind, and a straight section of the beach. Where the coast line is rugged, the winds are subject to many microscale variations, and slope or valley winds may also complicate flow patterns.

Sharp humidity lapses found with land and sea breeze circulations may form strong refractive gradients or modify existing refractive conditions. If there is a strong off-shore movement of dry air aloft, a boundary region between the two adjacent air trajectories may form. It is a front-like disturbance and is generally called a sea-breeze or coastal front. The warm air is above the cooler ocean air, and superrefraction may occur. This type of disturbance appears to be quite common along the western, southern, and eastern Australian coasts (Jenkinson, 1966) and coastal paths in New South Wales frequently show superrefraction due to this type of front.

5.4 Thunderstorms

A considerable reduction in range of radio transmissions (such as radar) may be caused by the attenuation of the radio signal by the heavy rain found near the center of a mature or dissipating thunderstorm cell. The effect is more severe for short wavelength radars such as the 3.2 cm, than for the 10- or 23-cm radars. However, strong refractive or ducting gradients have been found in the neighborhood of thunderstorms, primarily in the southwest quadrant of weakening storms.

Coons (1947) stated that an abnormal moisture lapse near the ground, due to the evaporation of rainfall, was the major cause of these ducts. However, the duct formation is also affected by the cooling of the earth's surface by the downdrafts from the thunderstorm. If low stratus clouds and light winds are present, the superrefractive effect may last for several hours.

5.5 Coastal Stratus

Along coast lines, where warm continental or other subsiding air may overlie the moist maritime air near the surface, the base of the superrefractive layers is usually near the top of the stratus deck. This is the case in the vicinity of San Diego, California, where the refractive layers are associated with the trade wind inversion (Moreland, 1965).

5.6 Foehn Winds

A foehn wind is a warm, dry, downslope wind observed on the lee side of mountain ranges. The name originated in the Alps, where such winds occur frequently. The advection of warm, dry air causes surface or slightly elevated superrefractive layers to form as a result of the moisture evaporated from the generally snow-covered surface. In the United States this effect is found with the chinook winds just to the east of the Rocky Mountains, especially in the winter and spring.

5.7 Fog

Refractive index conditions in fog vary from subrefractive to superrefractive. In the layer itself, the temperature or humidity gradients are not likely to be strong enough to form significantly intense refractive gradients, and either standard or substandard propagation conditions might be found. Just above the fog layer, however, there is frequently an appreciable decrease of humidity with height which may lead to the formation of a radio duct. Radiation fog, which forms on clear nights having light surface winds, is a type of fog frequently associated with superrefractive layers. Since this is a shallow fog, there is little effect on propagation conditions unless the transmitting and receiving antennas are relatively close to the ground.

5.8 Fronts

Significant refractive gradients may form along an upper front (frontal surface aloft), but the more usual effect of a frontal passage, especially a cold front, is to establish standard propagation conditions in the frontal zone because refractive layers tend to be destroyed by the turbulence normally accompanying a frontal passage. For example, on a 55-km line-of-sight path in Japan, Ikegami et al. (1966) found that marked fading (which had been observed for two consecutive nights) disappeared after a cold front crossed the path. Anomalous propagation is frequently observed, however, when subsidence occurs in a drier air mass that moves into an area after a cold frontal passage. Sea breeze or coastal fronts may cause superrefractive conditions also, especially in the lower latitudes (sec. 5.3). Brief periods of high radio signals have been observed with the passage of squall lines (Arvola, 1957). Immediately after the passage of the squall line, subsidence frequently occurs before the arrival of the associated cold front. The high moisture content of the surface air and the overlying drier air favor the formation of elevated superrefractive layers.

5.9 Low-Level Winds

Rider (1958) stated that the wind velocity was the most important meteorological factor not included in the formula for the radio refractive index, and a number of other investigators have studied the effect of the wind on microwave propagation.

Fengler (1964) in studies of a 202-km transhorizon path at 500 MHz, found that the wind velocity (at the altitude effective for wave propagation) is a criterion for the propagation mechanism and the field strength level to be expected. Where intensive and strong refractive index inversions are noted, reflection, refraction, and ducting are the prevailing propagation mechanisms, and high field strengths will be observed. But high winds destroy inversions, and scattering or diffuse reflection becomes the dominant propagation mechanism, with lower field strengths. No high field strengths were observed during periods of high winds in these experiments in Germany, but both high and low fields were observed with light winds. Fengler studied both the component of the wind parallel to, and normal to, the path. There was dependency of fading frequency with the component of the wind parallel to the path, but a correlation coefficient of 0.84 was obtained when the component of the wind normal to the path was considered. When a well-mixed atmosphere was examined (no strong refractive gradients below 1500 m), the correlation coefficient was 0.93.

Doherty and Neal (1959) suggested that a correlation coefficient near unity could be found between the surface wind and the fading rate when a time advance of about 2 hr was applied to the fading rate record. They regard the surface wind to be, in part, a measure of the hydrostatic instability of the atmosphere, and thus a measure of the higher turbulent velocities aloft. The 2-hr delay of the fading maximum behind the maximum wind is presumably due to the delay in transferring the turbulent energy from the ground to the height of the common volume (about 1500 m). Higher fading rates are also observed with the passage of rain through the common volume. Apparently this is caused by the high wind speeds and increased turbulence associated with the rains (Doherty and Stone, 1960).

Bauer (1961) examined the hourly values of the 10- to 90- percent fading range of selected 915-MHz troposcatter records of a 650-km path and determined that they showed behavior that correlated well with wind shear through the scatter volume. Although the wind data were gross scaled and taken at a point at least 112 km from the common volume, correlation coefficients of 0.76 to 0.8 were obtained. These results indicate that the fading range (10 to 90 percent) increases by 1.4 dB/(m/s)/km of average wind shear through the scatter volume.

Anderson and Gossard (1953) studied the effect of an oceanic duct upon microwave propagation using meteorological and radio data taken over Cardigan Bay, England. Data were taken at the ends of the path, averaged, and used to represent the entire path. This assumption was valid when there was a brisk breeze blowing from the ocean. When wind speeds were low, as in summer, heating over land during the day and subsequent nocturnal cooling caused an appreciable difference between the values of meteorological variables taken over the water and those taken over the sea. At a frequency of 10,000 MHz the agreement between theory and actual observations improved steadily as the wind speed increased. At speeds above 7 m/s the consistency was impressive. The authors noticed more scatter at 3345 MHz than at 10,000 MHz and the change to ducting conditions appeared to be more gradual; the 3345-MHz signals appeared to be influenced by the effects of the duct before the actual ducting occurred. This latter observation agrees with the accepted fact that stronger oceanic ducts are necessary to trap 3345 MHz than 10,000 MHz. Pickard and Stetson (1947), using a frequency of

42.8 MHz over a 270-km path in Massachusetts, observed that the best transmission (highest fields) occurred when the wind velocity was lowest, and the worst transmission (lowest fields) when the winds were strong. The turbulence accompanying the strong winds tended to destroy any laminar structure or favorable stratification in the lower atmosphere. They also found that the fields were higher when the direction of the flow of air was parallel to the path.

6.0 Attenuation of Radio Waves

6.1 General Comments

The attenuation of radio waves by clouds and precipitation is caused by both absorption and scattering. Attenuation of the higher frequencies is very sensitive since the attenuation is directly proportional to the amount of liquid water per unit volume and inversely proportional to the wavelength. Therefore, wavelengths of 1 cm or less (frequency ≥ 30 GHz) show a large amount of attenuation, but wavelengths of 10 cm or greater (3 GHz) experience a negligible amount of attenuation by rain and clouds.

Medhurst (1965) has pointed out that the numerical results for attenuation of centimeter radio waves from rainfall do not agree with those predicted by theory (Ryde and Ryde, 1945). There is a tendency for measured attenuation to exceed the maximum possible levels predicted by theory. Part of this discrepancy may be due to experimental error, especially with regard to the measurement of the precipitation rate. Under gusty wind conditions, the water density in the air (on the radio path), for a given precipitation rate on the ground, may be quite different from that under calm conditions. Also, the number of rain gauges is seldom adequate to insure that representative measurements can be obtained even when precipitation along the path is relatively uniform. Medhurst also states that part of the excess attenuation for the lower precipitation rates might be due to the presence of fog and mist, in addition to the precipitation, although this effect should be negligible for precipitation rates of 50 mm/hr or more, where large departures from the theory have been observed.

None of the above considerations adequately explains some of the extreme differences between the values of theory and measurements. In this regard Medhurst calls attention to the Hawaiian experiments using a wavelength of 1.25 cm as reported by Anderson et al. (1947). These experiments obtained results that have set them apart from other studies reported in the literature. First, the density of rain gages (nine along a 2-km path) was greater than in previous field tests, and second, only measurements made under uniform rainfall conditions were recorded. They found attenuations (dB/mi) between 1.5 and 2.0 times greater than the Ryde theoretical values.

Medhurst also suggested, because of the uncertainties in experiments, that it would be premature to attempt to modify the Ryde and Ryde theory (1945), but that it might be well to be aware of ways in which the present theory is lacking. He points out that the presently accepted theory does neglect multiple scattering effects along the path. The Ryde theory considers only the power removed by absorption and scattering from a plane wave by an isolated drop. This "subtracted" power is then summed over all the drops. There is the possibility that the rain structure might be more complicated than it is presently assumed to be. Dingle (1960) has suggested that precipitation may contain elements or clusters of two or more closely spaced drops, rather than the present concept of drops in a random pattern with average distance of separation greatly exceeding the drop diameters. Information is available that the distribution with time of the drops varies from what would be expected if the clustering did not occur. At this time it is not possible to draw any quantitative conclusions about the nature of clusters, but if clustering does occur, it could modify considerably the theory of rainfall attenuation of radio waves.

6.2 Attenuation by Rain

Saxton and Hopkins (1951) used a wavelength of 3.2 cm in studying the adverse effects of meteorological variables on maritime navigational radar. They observed that the greatest reduction in radar range caused by attenuation is the one caused by rain, such as that found in the tropical equatorial regions, e.g., the Indian and Pacific Oceans. Saxton states that a precipitation rate of 50 mm/hr might mean that a 10,000-ton ship would be detectable at a 6- to 9-km range instead of the normal detection range of about 25 km. However, with small targets, the masking effects from the precipitation itself rather than the attenuation is the important factor. As a result of rain echo, a ship of 1,000 tons would probably not be detected beyond 3 km instead of the normal range of 15 km.

Angell et al. (1958) also found that rain caused a depressed radio signal. In field experiments in England, using 3480 MHz over a 278-km path, the maximum fall in the median signal level in heavy rain was 15 dB, corresponding to an attenuation rate of 0.056 dB/km for the path. It is believed that the more important effect of rain is to cause a reduction in the efficiency of the mechanism involved in the scattering process.

Doherty and Stone (1960) observed the forward scatter from rain of 2720 MHz radio waves over a 145-km path near Ottawa, Canada. Their results support the assumption of omnidirectional scattering from rain. Two primary effects of rain on a tropospheric scatter path are the increased fading rate and the decreased bandwidth. The fading rate may increase by a factor of 10 or more, and pulse-to-pulse fluctuations have been observed at a pulse repetition frequency of 600 pulses/s. The 1.5-μs pulse is generally broadened to 3 or 4 μs, and at times, is broadened to lengths greater than 20 μs. Rain across, or close to, the path may at times be related to an <u>increase</u> in the signal level since: (a) energy may be scattered from the raindrops themselves, which for heavy rain might cause a change of as much as 12 dB, and (b) an increase in signal level may be associated with the elevated superrefractive layer formed at the boundary of the cold air flowing from the base of the thunderstorms.

6.3 Attenuation by Hail

The attenuation effect of hail depends on the size of the hailstones and the total amount of hail, however, hail produces less attenuation than an equivalent amount of rain. Since the hailstones grow to larger sizes than the raindrops, it is possible to get more backscattering from large hailstones than from raindrops with an equivalent amount of water content.

6.4 Attenuation by Snow

Snowflake attenuation is caused partly by scattering and partly by absorption. If the snow is dry, the attenuation is considerably less than that from raindrops having the same water content. However, with melting snow or ice particles the attenuation can be quite large, especially at shorter wavelengths (Battan, 1959).

6.5 Attenuation by Fog

Kiely and Carter (1952) observed that fog may cause an attenuation of 3-cm transmissions of about 0.2 dB/km when the visibility was reduced to an optical (visual) limit of about 33 m on an overwater path.

Saxton and Hopkins (1951) observed that dense fogs, especially in the polar climates, can appreciably reduce the maximum range for radar targets. With optical visibility of about 30 m, a radar range of 50 km could be reduced to 30 km for a 9375-MHz frequency. However, a normal range of 25 km should not be materially reduced unless the optical visibility is reduced to a few meters.

6.6 Forest Effects on Propagation

Head (1960) studied television reception at 482 MHz in a wooded area over distances of 12 to 23 miles. His observations indicated that the depression of signal level below the calculated smooth-earth field was more or less independent of distance, and ranged from about 22 dB with 50 percent tree cover to 30 dB with 100 percent cover. Forest attenuation may thus be one of the most significant factors in average loss of signal at the higher frequencies, with a seasonal variation related to changes in foliage.

Trevor (1940) measured attenuation of a 500-MHz signal through 500 feet of woods and underbrush; in summer the attenuation was 17 to 19 dB and in winter 12 to 15 dB as compared to propagation over treeless level ground. The vegetation was sufficiently dense so that the view of the transmitter was obstructed even when no foliage was present. Transmissions over a 500-ft span just above a low growth of scrub pine in July showed attenuation of 6 to 8 dB, possibly because of ground ray reflection rather than absorption.

Attenuation through trees is apparently a function of frequency. Saxton and Lane (1955) reported that thick and extensive woods could cause attenuation of the order of 0.02 dB/m at 30 MHz and 0.5 dB/m at 3000 MHz (based on measurements in summer with mostly deciduous trees).

Over forests with a dense leaf canopy, solar heating produces temperatures at the tree crown level that are higher than those at the surface of the ground during the afternoon. At night, radiational cooling frequently results in a lower minimum temperature at about the canopy level than those at the ground or in the air immediately above the canopy. Behn and Duffee (1965) have measured a temperature inversion of 3.5°C in about 16 m just above a dense forest canopy during evening hours.

The formation of such inversions, below the canopy in the afternoon and above the canopy at night, may lead to anomalous propagation in forest or jungle areas. Baynton et al. (1965a) reported difficulty in radio communications at 7567 MHz between the ground and low-flying aircraft over a tropical rain forest. He attributed this to the possible formation of a ground based radio duct beneath the tree canopy during the daytime.

7.0 Observations of Radio Performance Related to Large-Scale Weather Systems

7.1 Air Mass, Seasonal, and General Effects

The effect of air masses upon radio propagation is chiefly related to the vertical distribution of temperature and humidity within the air mass, and therefore any mechanisms that change these gradients (such as subsidence, radiation, and convection) also modify the radio propagation characteristics of the air mass. Because similar air masses tend to modify in somewhat similar fashion, it has been possible to obtain correlations between air mass types and radio propagation effects.

Among the earliest studies of the tropospheric radio-weather relationships were those of Ross A. Hull in the period from 1934 to 1938 (reported by Friend, 1945). Using a 60-MHz system on about a 160-km path near Boston, Massachusetts, he found, for example, that nighttime signals were much higher in summer than winter, and that there was less diurnal change in winter. The periods of very highest signal level invariably accompanied atmospheric conditions resulting in rain. With fresh polar air over the path, signals were low and subject to rapid fading. As the air modified, the signals took on a more ragged character but attained higher levels. With warm tropical air spreading over the region there was a tendency for minor fading fluctuations to become grouped and show a longer period, possibly related to wave motion on a frontal surface. For 3 or 4 hr before the start of the frontal precipitation, signal levels were high, then fading increased and the signal level dropped as the precipitation started. The turbulence in fresh polar air as it moved under warmer air resulted in rapid fading, but a diurnal effect was noted, in that cooling at night reduced the turbulence, and the signal became strong and steady.

Doherty (1964) found that significant differences in signal strength and variability at 2720 MHz on a 144-km path in Canada were due to the type of air mass over the station. In winter, periods of superrefraction were generally found with maritime arctic air because it was relatively dry and radiational cooling could occur at night. The temperature inversion developed during the night could persist during the day because of the lack of solar heating of the highly reflective snow-covered surface.

Continental arctic air was characterized by low signal levels with little, if any, nocturnal cooling because the air mass was apt to be much cooler than the surface and a ground-based temperature inversion was unlikely to develop at night. Maritime polar air seemed to be intermediate in its characteristics when compared with maritime arctic and continental arctic air masses. Maritime tropical air generally showed a relatively high signal, but no superrefraction was observed. These latter conditions were related to the high humidity of the air mass inhibiting radiational cooling.

Anan'ev and Troitskiy (1964) have reported results of measurements at 30 cm over a mountain diffraction path between Alma-Ata and Frunze, Kirgizskiy SSR. On this 192-km path no connection was found between fading and the time of the day. The fading depth increased after rain and decreased in periods of settled dry weather.

Kalinin et al. (1964) made statistical studies of measurements on tropospheric relay links in the central part of the USSR. These measurements were made over many hundreds of hours on each route at different seasons and over several years. The routes varied in length from 159 to 730 km at wavelengths of 30 to 40 cm, and from 85 to 303 km at 8-to 9-cm wavelengths.

For distances in excess of 300 to 400 km, the attenuation was observed to be higher in summer than in winter, but this seasonal variation became smaller as the range increased (e.g., at 300 km the seasonal variation was 15 dB while at 630 km it was 7 dB for 30-to 40-cm circuits). At 8- to 9-cm wavelengths the attenuation was 1 to 15 dB higher in summer than in winter. The attenuation was 6 to 12 dB greater at 30 to 40 cm than at 8 to 9 cm for ranges of 150 to 300 km. Slow fades (greater than 5 to 10 min duration) over different sections of a tropospheric relay link were found to be statistically independent. The duration of rapid fades on a 303-km route decreased at the shorter wavelengths.

Regardless of the season, the mean signal level increased and the depth of fading decreased during stable weather conditions. When either a warm or cold front passed across the route, the mean signal level fell sharply (10 to 20 dB). After the front passed, the signal level was slowly restored. It was found that the signal variations were connected more with the variability of the weather than with the nature of other conditions, such as cyclonic or anticyclonic pressure systems. No definite relationship was discovered between the signal level and any one meteorological parameter, including those with clearly marked diurnal variations, but there was a slight tendency for the signal to fall in the daytime, especially in the summer. There was no marked correlation between the mean signal levels and the dielectric constant of air near the earth at the middle of the path. Kalinin considers the reports of other investigators on correlations of mean signal levels and dielectric constant over long periods of time to be misleading, in that this merely reflects the fact that they are both subject to seasonal fluctuations.

Chisholm et al. (1962) have reported on propagation losses observed on several 400-MHz paths along the east coast of the United States, varying in length from 98 to 830 mi. Comparing 188-, 350- and 618-mi paths, they found median signal levels to be highest in summer and the seasonal differences greater at 188 mi than at 618 mi. The 188-mi path showed about a 20-dB lower median signal level in April than in July, while the difference at 618 mi was less than 5 dB.

Peterson et al. (1966) found that a prolonged outage on a 5 GHz, 404-km, obstacle diffraction path in Europe was closely related to depression and distortion of the radio beam caused by elevated super-refractive layers. These layers were probably formed when dry air on the lee side of the Alps moved over a moist coastal air mass. The southern terminal of this path is only 11 km from the sea, and is affected by a sea breeze circulation when the region is under the influence of weak-gradient high pressure systems.

7.2 Pressure Systems and Fronts

In general, polar highs consist of air that is too cold and dry to produce strong refractive gradients capable of trapping microwave transmissions. However, if these highs pass over a warm body of water, the lower layers may gain enough heat and moisture from the water to form elevated superrefractive gradients (Arvola, 1957).

A warm high may produce a pronounced elevated superrefractive gradient because of the combination of sinking air, a usually moist layer beneath the inversion layer, and the overall warmth of the air mass. Warm highs are also associated with a surface temperature inversion (usually nocturnal). The warm air mass above the inversion is dry because of the subsidence or advection of warm air. In the case of a weak flow of warm air it is possible for a subsidence-formed refractive layer to lower and merge with a surface-based inversion (Arvola, 1957).

Dennis (1961) studied the correlation of hourly median signals and refractive gradients over a 480-km scatter path from Florida to the Bahama Islands. There were no diurnal effects observed since diurnal temperature changes are at a minimum over the oceans. Signal levels were higher in the summer than in the winter but a drop of about 15 dB in 3 hr was observed after a cold frontal passage, as dry air replaced the maritime air. Dennis obtained a correlation coefficient in this study of about 0.85, using surface values of refractivity to predict signal levels.

He also studied a San Diego to Santa Anna, California, path of about 135 km. The best correlation between the basic transmission loss and change in refractivity in the first kilometer on this circuit was in February, and the poorest was in August. The mean basic transmission loss for May was 10 dB less than that for November. Dennis believes that a 48-hr forecast of refractivity for basic transmission loss calculations could be made to within ± 5 N-units, and a 72-hr forecast to within ± 10 N-units. Beyond these periods it would be better to use climatological data.

Ugai et al. (1961) observed that fadings were infrequent during inclement weather in Japan. However, remarkable fadings occurred in the fine weather accompanying periods of high pressure in the area. During frontal passages no fading was noticed but strong fadings occurred in the high pressure cells following a cold frontal passage. Surface temperature inversions appeared at night as a result of nocturnal radiation, but some were seen in daytime hours. During May through August, radio ducts of 20 to 50 m in depth were almost continually observed. The strength of the duct depended on the humidity lapse during the summer and the temperature inversion during the winter.

Hirao et al. (1952), using frequencies of 150 MHz and 65 MHz over a 125-km path near Toyama Bay, Japan, found that field strength was high in summer, and low in winter and on days with precipitation. Highest fields were observed when a migratory high spread over the path, probably because of the effect of subsidence. The vertical distribution of refractive index was almost linear in winter, but was more complicated in the spring and summer. Abnormally high field intensities were more prevalent during the night than during the day; however, when such conditions appeared, they seemed to occur on succeeding days at about the same time. Fronts caused abnormally high signals with large variations, and the frontal effect was more noticeable at night than during the day. The cold front had a greater effect than other types of fronts.

Spencer (1952) studied radio propagation at 89 MHz over a 272-km path in England with regard to the effect of synoptic weather conditions. He found that isothermal temperature profiles or inversions may have a pronounced effect on the field strength, and that curvature of the isobars (indicating whether high or low pressure was over the path) had a somewhat less important effect. He also observed that high field strengths are twice as likely to occur with high pressure as with low pressure patterns. The resultant refraction, which varies with the type of weather conditions present, may cause the field strengths at 200 to 300 km from the transmitter to be as high as the normal level at 50 to 100 km.

Duct thickness for Spencer's test area was found to be about 100 m. Ducts with a thickness greater than 100 m are apparently quite rare in England. Fifty-six percent of the high field strength periods were associated with strong elevated refractive gradients in the absence of surface gradients; 35 to 45 percent of the elevated layers were found to be between 800 and 900 mb (1950 - 950 m), but the strong refractive gradients were found mainly at somewhat lower elevations (950 - 900 mb or about 490 - 950 m). Some high field strengths occurred with easterly and southerly winds associated with low pressure centers, but a great majority of high field strengths were related to high pressure conditions.

The sector of a high pressure cell in which the greatest amount of subsidence is occurring may be fairly well established by considering the temperature regime toward which the cell is moving. Flavell (1964) pointed out that the northerly winds found on the eastern side of high pressure cells in the Northern Hemisphere are usually moving toward warm surface temperatures. This tends to increase the convection effects, which, in turn, lifts the boundary layer between the relatively cool, moist surface air and the warmer, drier upper air, and thus weakens it. On the western side of the high pressure cell the boundary tends to be lower and more pronounced since there is less convective activity. The greatest change in refractivity associated with the boundary layer in the northwest of Europe occurs on the western side of high pressure cells.

Joy (1958) made a series of tests over a mixed land-sea path ranging in length from 90 to 320 km, using a frequency of 9375 MHz. The average signal level was found to be some 10 to 15 dB below that predicted from theory. A prolonged fade was noticed at a range of 165 km and attempts at radio reception at 320 km on overland paths were unsuccessful, possibly because of the frequent occurrence of intense, extensive high pressure systems over the British Isles during the tests. Joy found that periods of normal radio propagation occurred with low pressure systems, and poor propagation conditions were observed only in the presence of high pressure systems. In contrast to the radio reception over the land paths, excellent radio ranges were observed over the English Channel during the presence of a ridge of high pressure. Joy assumed that this effect was due to the formation of a well-developed evaporation duct, since terminal heights were both rather low.

Hay and Poaps (1959a), using a frequency of 2000 MHz over a 34-km path near Ottawa, Canada, studied fadeout of radio signals. During the period of their experiments 64 percent of the fadeouts occurred near a center of high pressure and 30 percent with slowly changing transitional periods between centers of high and low pressure systems. The remaining 6 percent of the fadeouts occurred shortly after a low pressure center moved through the area.

Stark (1965) conducted experiments in the North Sea at 560 MHz and 774 MHz with a path length of 194 km and 950 km. He found that the slow-fading type of signal was normally associated with the higher levels of field strength, and was observed during periods of high atmospheric pressure. The fast-fading type of radio reception was found with low field strengths and was observed during periods of low atmospheric pressure. The height of the superrefractive layer was about 500 m.

Anastassiades et al. (1962), using a frequency of 2005 MHz, conducted radio experiments with concurrent meteorological observations on a 129-km path in Greece, and found that northerly winds blowing out of a high pressure area in winter gave a radio reception that was rather smooth with no deep fades (less than 5 dB). The air masses associated with these winds were mainly cold, dry, polar continental types, which were warmed from below over the Aegean Sea, and consequently no inversions could develop. He observed that when the path was in the warm sector of a low pressure area the fading amplitude reached as high as 30 dB, particularly in winter and spring when the sea surface was colder than the air in the warm sector, allowing inversions to develop rapidly. Similar fading was observed under calm, clear conditions when ground temperature inversions developed.

The passage of a cold front or low pressure across the area was usually accompanied by an increase in fading, but when winds shifted to the north after a cold frontal passage, the radio reception again became smooth (low fading). Changes in the type of fading were also observed with changes of wind direction and passage of fronts or low pressure centers. Receptions with 30-dB amplitude variations were frequent from April to July and were observed with sea breezes and the Etesians; the latter are northerly winds in the summer in the eastern Mediterranean, which transport warm dry air masses from the mainland over the cooler sea.

Doherty and Neal (1959), using a frequency of 2720 MHz on a 315-km path between Ottawa and Toronto, Canada, observed that the passage of a cold front across a radio link resulted in a disturbed signal with excursions of 5 to 15 dB from the short-period median level occurring over an interval of 5 to 10 min. This was quite different from the usual stability of the signal which generally showed a 1- to 2-dB variation over a 10-min period. The fading rate generally, but not always, increased with the signal level changes.

Hay and Poaps (1959b), using a frequency of 500 MHz over a 137-km radio path near Ottawa, Canada, observed that the signal fading rate rose above the normal diurnal maximum when the radio path was disturbed by fronts. The fading rate appeared to reach a maximum when the boundary of the frontal zone was about 900 m above the center of the path. The fading rate remained high as long as any part of the frontal zone was between the surface and about 1000 m. They found that the effect of a front on radio transmissions evidences itself by an increase in the rate of fluctuation and a decrease in the mean amplitude of the signal. In one case the fading rate was as high as 100 a minute and remained high for 4 hr or longer. Cold fronts appeared to have a greater effect on signal amplitude than warm fronts, with the variation being greater at night than in the daytime. Precipitation alone had little effect upon signal transmission. Only 12 percent of the maxima in fading rate occurred when rain fell on a major part of the path, and only 6 percent when snow fell. There were 102 prominent low pressure centers observed along the radio path in the 306-day test period, and 62 of these centers were accompanied by an abnormally high fading rate in the radio signal within 12 hr.

Hay and Poaps observed a somewhat higher degree of correlation between the disturbance of the signal and shallow depressions of pressure such as those accompanying cold frontal passage. A decrease of 2 mb in surface pressure with respect to the normal trend generally lasted from 1 to 2 hr. In 306 days of tests some 120 instances of shallow pressure changes were observed and the signal fading rate reached a maximum within 12 hr in all but two cases. They suggest that it is primarily the structure of the frontal zone, and not the precipitation or the vertical movement of air associated with the low pressure center, that affects the radio transmission.

Pickard and Stetson (1947), using a frequency of 42.8 MHz over a 270-km path in Massachusetts, found that all types of frontal passages lowered signal levels and, apparently because of the waveguide effects, the amount of signal depression caused by the passage of the front varied with the angle made by the front with the path. They found that when the front was parallel to the path the field was least depressed, and that when the front made a considerable angle with the path, the signal was depressed to the greatest extent. It was also noticed that the high fields were usually followed by an increase in the surface temperature along the path, the temperature reaching a maximum about 30 hr after the field maximum. Low fields were generally followed by falling temperatures, which reached a minimum about 30 hr after the minimum signal strength was reached. Pickard and Stetson found that occluded fronts had little effect on signal strength. Only a few (8) warm fronts were observed during the period, but these produced a depression in signal strength to about 80 percent of normal. Cold fronts making an angle greater than 30° with the path produced a drop in field strength to 74 percent of the normal value; cold fronts making an angle between 0° and 30° decreased the signal strength to 84 percent of its normal value; cold fronts parallel to the path gave a reduction in signal strength to 91 percent of the normal value.

Sabin (1966) investigated radio outages that occurred in late winter and early spring months on a 900-MHz troposcatter circuit between England and Spain. He concluded that a large proportion of the communications outages on this 800-km path were probably caused by extensive superrefractive layers and ducts, which bent the radio rays so that they did not reach the proper height for scatter propagation. However, there were some outages for which no meteorological explanation could be found in the available data. Sabin made an analysis of synoptic weather patterns associated with the outages, as well as calculating refractivity profiles from the radiosonde observations made at three points near the radio path. He found two high pressure and three low pressure situations which were associated with the radio outages; subsidence was an important factor in many cases, and he found that propagation conditions improved as a cold front crossed the path. All the important refractivity changes occurred below the 700-mb level (about 3 km), and most of the outages took place when highly refractive layers occurred between 950-700 mb (0.4 - 3 km) at more than one of the radiosonde stations along the path. Surface ducts (below 950 mb) appeared to have little effect on this circuit.

7.3 Monsoons

Monsoons are similar to land and sea breezes in that they are caused by the difference in the temperature of the air over land compared with the temperature of the air over water. However, monsoons commonly affect a much larger area, and are seasonal rather than diurnal in character. Monsoons are most prevalent where the largest land masses border the largest bodies of water, e.g., the East Indian section of the Asian continent. Well pronounced monsoon circulations also occur in Australia and North Africa. In the Americas and Europe there are also tendencies for such circulations (chiefly in the summer), but they are much less common and less well developed than in India. Raghavan and Soundararajan (1962) reported that for the area around Madras, India, propagation of radio waves was generally standard in the monsoon season (June to September). In October, conditions occasionally became superrefractive and strong superrefractive gradients were most commonly observed in March and April.

7.4 Trade-Wind Regions

The trade winds, which are found between about 30°N and 30°S (chiefly over the oceans), are an important factor in microwave propagation because they are associated with regions of extensive and persistent elevated superrefractive and ducting gradients. The trade wind inversion is the interface between the dry subsiding air of the semipermanent subtropical high pressure cells and the relatively moist and turbulent low-level maritime air in the lower trade wind circulation. The trade wind inversion has a mean thickness of about 400 m. The height is a measure of the depth to which the upper current has been able to penetrate downward, and as such is an indication of the degree of subsidence or the probable intensity of the temperature inversion.

Investigations have been conducted in the trade wind areas by many research groups. Ringwalt et al. (1958) found a strong superrefractive gradient at a height of about 1500 m off the east Florida coast that was associated with the trade wind circulation. Katzin et al. (1960) made aircraft flights between Brazil and Ascension Island, using both radiosonde and refractometer equipment. The results indicated that an elevated duct was present most of the time and that radio frequencies above 200 MHz should be affected. The greatest radio ranges were observed when both the transmitter and receiver were in the ducting layer, which generally had a thickness between 300 and 400 m. The base height was about 1300 m in January (summer) and 1800 m in July (winter).

Ringwalt and MacDonald (1961) made additional studies between Brazil and Ascension Island and confirmed the existence of ducting layers in that area. They found that the best month for [illegible]nded ra[illegible] ranges was November, when the base height of the ducting layers was about 1800 m. The results of this study indicate that under favorable conditions of active subsidence a radio duct was present about 80 percent of the time, and that when subsidence conditions were not favorable, la_ers of ducting strength were observed about 40 percent of the time.

8.1 Forecast Accuracy

No standard method of forecast verification exists, and quoted figures on accuracy may be misleading unless the forecast circumstances and verification limits are considered. Verification systems that consider a sufficient number of factors to be meaningful tend to be complex and time-consuming, while the simpler systems yield results that may be heavily biased or erroneous. In general, it is considered that a verification of 50 percent or less represents guess work or zero forecast skill (Willett, 1951).

Different weather elements offer different degrees of difficulty to the forecaster. A 2-day forecast of daily average temperature is generally quite easy compared with a 12-hr forecast of cloud heights or wind speed and direction. The type of forecast required for radio-meteorological purposes involves meso- or micro-scale considerations, e.g., the elevation of inversion layers relative to a given set of antennas, changes in flow patterns caused by mountain ridges or valleys, local changes in air mass properties caused by heating or cooling of land or water surfaces, effects of turbulence and mixing, etc. In many cases the basic data upon which such a forecast must be based are simply not available, or may be lacking in detail (e.g., data on upper air structure).

An analysis of weather forecasting made by Willett (1951) indicates that:

(a) Detailed aviation forecasts, including predictions of wind speed and direction, cloud heights, visibility, type of precipitation, icing and turbulence hazards, fog, etc., may be made for periods up to about 18 hr with a verification of 90 to 95 percent on a 50 percent probability basis of verification.

(b) From 12 to 48 hr, forecasts for specific geographical areas of the day-to-day sequence of those aspects of weather which materially affect human activity and well being (degree of cloudiness, probability of precipitation, temperature range) verify from 70 to 90 percent with skill decreasing as the period increases.

(c) Forecasts of the day-to-day weather sequence show negligible skill beyond the fourth day in advance. Predictions of temperature and precipitation anomalies for 5 to 7 days in advance verify at about 70 to 75 percent for temperature but only about 60 percent for precipitation.

Aviation terminal forecasts, giving details similiar to (a) above, are prepared each 6 hr for 12-hr periods at forecast centers of the U. S. Weather Bureau. In a study of the utility of these forecasts to aviation interests, it was found (Kerr et al., 1962) that during poor weather conditions the accuracy of the forecasts declined considerably from the overall averages usually quoted. In forecasts of cloud heights when the cloud ceiling was below 4000 ft the average accuracy of 21 stations for a 3-yr period varied from about 68 percent at the start of the forecast period (0 hr) to 52 percent at 3 hr, 43 percent at 6 hr, and 37 percent at 12 hr. Under still poorer weather conditions, ranging from low visual flight conditions down to below instrument flight minimums, the 21-station average of ceiling and visibility forecasts showed the percent of hits as follows: 0 hr - 49.4 percent, 3rd hr - 31.1 percent, 6th hr - 24.2 percent, and 12th hr - 19.0 percent.

It should be noted that there is normally several hours time lag between the weather observation and issuance of the forecast. This delay is a result of time requirements for data transmission and relay, data plotting and analysis, forecast preparation, and transmission of the forecast to the users. Also, a forecast that falls outside the acceptable limits of a particular verification system may still be of considerable operational value if the trends in the weather have been predicted. For example, the timing of a frontal passage may be in error so that at verification time the forecast is wrong, but expected low ceilings do arrive an hour or so later.

The American Meteorological Society (1963) issued a policy statement on weather forecasting which made the following comments:

"The usefulness of weather forecasts depends both on their accuracy and the manner in which the forecast information is used. Although the accuracy of all weather predictions deteriorates with time, forecasts of low accuracy can be useful and economically beneficial when properly applied. The forecast accuracy attained by such procedures as predicting that the weather will remain unchanged (persistence) or by predicting normal weather occurrences based upon past weather records (climatology) or simple variations on these procedures serve as scientific bases for measuring forecasting skill. Unless forecast accuracy exceeds the levels achieved by basic methods such as these, forecasting skill cannot be said to exist. Statements of high levels of forecast accuracy do not necessarily imply skill, since similar accuracy may be achieved by proper use of simple climatology or persistence. The skill factor in weather forecasts can be expected to vary depending upon the meteorological situation, geographical area, and season."

The American Meteorological Society feels that the preparation of acceptable forecasts requires professionally trained personnel. Forecasts prepared by people so qualified can be expected to achieve the following levels of skill and usefulness:

"For periods up to 24 hr, skillful weather forecasts of considerable usefulness are possible. Within this interval detailed weather and weather changes can be predicted. Hour-to-hour variations can be predicted during the early part of the period.

"For periods extending to about 72 hr, weather forecasts of moderate skill and usefulness are possible. Within this interval, useful predictions of general trends and weather changes can be made.

"Average weather conditions for periods of about a week can be predicted with reasonable skill. Beyond 3 days, skill in day-to-day predictions is small.

"Average temperature conditions for periods up to a month can be predicted with some skill. Day-to-day or week-to-week forecasts within this time period have not demonstrated skill."

8.2 Forecasting Procedure

In forecasting for a particular application, e.g., frost-damage to fruit or vegetables, the first step is to determine the probable movement of the larger or gross-scale synoptic features, such as large highs, intense lows, strong frontal systems, upper-level flow patterns, etc. Next an estimate is made of the effect the movement of these large-scale features will have on the weather elements in a given locality. Increasingly smaller-scale features may then be considered, such as diurnal changes in local wind flow (as in the case of valley and mountain winds or land and sea breezes) or the drainage of air into lowlands near lakes or rivers, local modifications resulting from snow cover, warm or cold water surfaces, vegetation, etc. Because of the lack of both data and exact mathematical means of handling the data if it were available, the prediction of smaller-scale weather processes is largely subjective, and quantitative forecasts are made by empirical methods based upon observed synoptic-climatological relationships. For example, a frost forecast in a particular synoptic situation might depend upon a certain direction and speed of wind at an observation point, such as a nearby airport weather station, the amount of cloud cover expected, the temperature-dewpoint relationship at a given time of day, etc. For two orchards or farms close together, but at different elevations or in different types of terrain, the prediction would undoubtedly be different. Even two points in a relatively small orchard might be affected differently if there were a steep slope to the land. Most important of all, the end product in this case is an estimate of the effect certain temperatures will have on the fruit or other crop. A temperature of $0^{\circ}C$ may cause rapid damage to one plant variety, while another variety may safely withstand such temperatures for many hours.

Similarly, in radio propagation predictions, once the small-scale weather features in a given locality or along a particular circuit have been forecast, it becomes necessary to determine the effect of these conditions at particular frequencies with antennas at certain heights or locations, at particular transmitter powers and desired bandwidths. In all types of forecasts, the application of the forecast is an important consideration both for the forecaster and the user. The fruit-frost forecaster may recommend use of heaters or wind machines if critical temperatures are predicted; the aviation forecaster may suggest a change in flight altitude or routing if he predicts severe thunderstorms or icing. The radio-meteorologist must also consider the possibilities of rerouting, rescheduling, or other ways of making optimum use of available weather information, so that he can properly advise the operations staff.

Attempts have been made to classify radio refractive conditions in various air masses. While this seems like a promising first step in the forecast process, in practice it presents many difficulties. The ideal or "classification" air mass type may be subject to wide variations even in the source region, and will be subject to constant modification in moving across any land or water surface. The prediction of vertical air structure, based upon synoptic reports and without regard to air mass classification, is probably a more realistic approach in that it avoids the errors due to faulty initial classification. In other words, if a given vertical air structure prevails in an area, it affects radio waves in the same manner regardless of whether the air mass is classified as of maritime tropical or continental polar origin.

8.3 Types of Forecasts Considered Feasible

The results of this survey of observed radio-weather relationships are summarized in table 1, pages 75 to 83. Considering both the information contained in this table and the current state-of-the-art in the field of weather forecasting, it appears that only very general propagation predictions could now be made, based upon weather forecasts. The small-scale fluctuations in atmospheric flow processes, which are probably responsible for short-period changes in signal level, cannot be forecast except in a very general way. For example, it is possible to predict the approximate time of convective activity and average and peak wind speeds, but not the minute-to-minute values of updrafts or wind speeds. However, useful applications of forecasts might be made in certain areas or on certain circuits, such as the following:

(a) Trade wind inversion. Estimates of general refractivity conditions in some parts of the trade wind belt, such as between southern California and Hawaii, should be possible for periods of up to a few days. Specific refractive layer intensity and height probably could not be forecast more than 12 hr in advance.

(b) High pressure areas. Predictions of the approximate location of large high-pressure areas--the type likely to be associated with extensive subsidence--can be made for periods of 1 to 3 days in most areas. Semipermanent high pressure cells (such as the "Siberian" high, "Bermuda" high, etc.) may at times be predicted for longer periods --possibly up to a week. The location of inversion layers and significant refractive layers associated with these large highs is probably predictable for not more than 12 hr in most cases. In other words, a general relationship between a high cell and propagation might be predictable for periods up to several days, but ducting or superrefraction at a certain level that would produce critical bending on a particular circuit might be predictable for only a few hours.

(c) Low pressure areas and frontal systems. Over populated land areas the approximate location of low pressure centers and fronts may be predicted for about 24 hr. In some cases the location of a very intense low might be predicted for longer periods, possibly two or three days. This would also be true of the semipermanent low-pressure areas such as the so-called "Aleutian" or "Icelandic" lows. Diffuse and slow moving fronts such as commonly occur in summer are usually more difficult to predict than the high-contrast fast-moving fronts of temperate zone winters.

(d) Radiation inversions (and associated refractive gradients). These are predictable for a local area for not more than 12 to 24 hr; the great influence of local factors (e.g., drainage and other meso- and micro-scale winds, snow and vegetative cover, cloudiness) on radiational heat losses makes it difficult to predict inversions of this type for other than small areas in which the forecaster has both extensive data and considerable experience.

(e) Elevated inversion layers. Except in trade wind zones, these are probably almost unpredictable with present sparse upper air observations, and in any case for not more than 12 hr.

(f) Diurnal variations in median field strength, fading rate, fading depth. Probably unpredictable at present. Diurnal variations in certain weather elements (temperature, humidity, winds, etc.) can be predicted, but the radio-meteorological correlations are not known sufficiently well to permit forecasts of field strength on any but a very crude basis.

8.4 Utility of Short-Period Forecasts

Short-period forecasts of radio-weather factors can be of definite value in various radar applications, where range and elevation corrections can be applied to fit the predicted refractive conditions. Forecasts may also be of some value in estimating communication reliability between aircraft or between aircraft and ground stations. In point-to-point radio services, it may be more difficult to derive significant benefits from radio-weather predictions. Some improvement in scheduling might be possible with accurate 24-to 48-hr forecasts, but the overall improvement in circuit efficiency might not justify the e' ort. If, however, outage periods could be predicted with a high degree of confidence, this information could be used to advantage in the scheduling of maintenance work. For example, if there are duplicate circuits available between two points and the prediction calls for poor propagation or a potential outage on one route, then it would certainly be prudent to forbid any routine maintenance on the other circuit during the period of predicted outage. The circuit managers of both circuits might also wish to make special efforts to insure that all equipment was "peaked up" to the highest level of operating efficiency before the time of predicted outage.

Of more immediate potential benefit to tropospheric communications is the application of radio-weather analyses in the planning and design stages of a radio circuit. Synoptic climatological data can provide important information on daily, monthly, and seasonal variations in weather on the planned circuit, which should be considered in determining the optimum siting for a particular area. For example, a study of the planned circuit may show a preferred elevation for the antennas, considering the average height of highly refractive layers in the area; it may indicate that weather patterns in a certain month are such that a definite change from yearly or seasonal average conditions is to be expected; it may show a pronounced diurnal change; or it may show a probability of severe wind, precipitation, icing, or temperature and humidity factors that would be reason for relocation or redesign of a station.

High incidence of subrefractive layers in an area may make it desirable to increase the design fading margin on a circuit; e.g., a transmitting antenna 50 m above a smooth earth would have a radio horizon of about 30 km with a "normal" gradient of about -50 N/km, but the horizon distance might be as little as 8 km under subrefractive conditions (Rice et al., 1966).

The casual application of weather factors to planning and design problems should be avoided, however, since misinterpretation of climatological data may easily lead to erroneous design conclusions. There may, for example, be ample statistical weather data available at a weather station quite near a proposed transmitter site, but when altitude, exposure, local wind factors, etc., are taken into account, the station data may be of only limited usefulness as an indicator of weather at the proposed site or along the circuit.

9.0 Conclusions and Recommendations

a. The regular prediction of radio performance, based upon synoptic meteorological and climatological data, is impractical at the present time. Meteorological data are probably inadequate for forecast purposes on many of the existing circuits, and sizeable commitments of personnel and equipment would be necessary to remedy this lack. However, the chief obstacle to a propagation prediction program based upon weather forecasts is a lack of knowledge of the precise effect of weather changes on specific circuits. Two circuits in the same general area may show very different response to a given weather situation because of differences in terrain, antenna orientation, antenna height etc.

b. Before forecasts should be attempted for operating circuits, the radio-weather relationships on each particular circuit need to be studied intensively -- i.e., radio data for all periods of the day and all months of the year should be available for study with detailed synoptic weather data for the area.

c. Radio data necessary for long-term studies of radio-weather relationships are difficult to obtain. Some system of regular sampling of fading rates, fade depths, and median field strength on operating circuits would be of very great value to radio-meteorological research.

d. Potentially greater benefits are likely from radio meteorological analyses during the circuit design process, than from short-range predictions after the circuit is in operation. Certain climatic factors or meteorological situations are known to increase the probability of anomalous propagation, even though a precise short period forecast of propagation (based upon weather forecast techniques) is not believed feasible at present.

10.0 Acknowledgment

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11.0 References

American Meteorological Society (1963), Policy on weather forecasting, Bull. American Meteor. Soc., 44, 445-446.

Anan'ev, K. N., and V. N. Troitskiy (1964), "Experimental study of the diffraction of ultrashort waves at mountain ranges," Telecommunications, Part 1, 18, No. 10, 1-5.

Anastassiades, M. A., L. N. Carapiperis, N. K. Kariambas, and P. G. Paraskevopoulos (1962), "Prediction of field strength fading forms by means of weather situations," Geofis. Pura. Appl. 52, 143-152.

Anderson, L. J., J. P. Day, C. H. Freres, and A. P. D. Stokes (1947), "Attenuation of 1.25 cm radiation through rain," Proc. IRE, 35, No. 4, 351-354.

Anderson, L. J., and E. E. Gossard (1953), "The effect of the oceanic duct on microwave propagation," Trans. AGU, 34, No. 5, 695-700.

Angell, B. C., J. B. L. Foot, W. J. Lucas, and G. T. Thompson (1958), "Propagation measurements at 3480 Mc/s over a 173 mile path," Proc. IEE, Pt. B, Supp. 8, 128-142.

Arvola, W. A. (1957), "Refractive index profiles and associated synoptic patterns," Bull. Am. Meteorol. Soc., 38, No. 4, 212-220.

Battan, L. J. (1959), "Radar Meteorology," 50, (University of Chicago Press).

Bauer, L. H. (1961), "Correlation of wind shear with tropospheric scatter signals," IRE Trans. (AP) 9, 466-470.

Baynton, H. W., H. L. Hamilton Jr., P. E. Sherr, and J. J. P. Worth (1965a), "Radioclimatology of a tropical rain forest," J. Geophys. Res., 70, No. 2, 504-508.

Baynton, H. W., J. M. Bidwell, and D. W. Beran (1965b), "The association of low-level inversions with surface winds and temperature at Point Arguello, California," J. Appl. Meteorol., 4, No. 4, 509-516.

Bean, B. R. (1954), "Prolonged space-wave fadeouts at 1046 Mc observed in Cheyenne Mountain propagation program, Proc. IRE, 42, No. 5, 848-853.

Bean, B. R. (1959), "Climatology of ground-based ducts, "J. Res. NBS 63D (Radio Prop.), No. 1, 29.

Bean, B. R., and G. D. Thayer (1959), "Models of the atmospheric radio refractive index," Proc. IRE, 47, No. 5, 740-755.

Bean, B. R., and R. E. McGavin (1965), "The use of the radio refractometer to measure water vapor turbulence, "Humidity and Moisture, 2, A. Wexler, ed. (Rheinhold Publishing Co. New York) 561-568.

Bean, B. R., B. A. Cahoon, C. A. Samson, and G. D. Thayer (1966), "A world atlas of atmospheric radio refractivity," ESSA Monograph No. 1, (U.S. Gov't Printing Office, Washington, D.C.).

Bean, B. R., and E. J. Dutton (1966), "Radio Meteorology, " NBS Monograph No. 92, (U.S. Gov't Printing Office, Washington, D.C.).

Behn, R. C., and R. A. Duffee (1965), "The structure of the atmosphere in and above tropical forests," Report No. BAT-171-8, Battelle Memorial Institute.

Burrows, C. R., and S. S. Attwood (1949), "Radio Wave Propagation," (Academic Press Inc., New York, N. Y.), 146.

Chisholm, J. H., W. E. Morrow, B. E. Nichols, J. F. Roche, and A. E. Teachman (1962), "Properties of 400 Mcps long-distance tropospheric circuits, Proc. IRE, 50, 2464-2482.

Coons, R. D. (1947), "Guided propagation of radar in thunderstorm conditions," Bull. Am. Meteorol. Soc., 28, 324-329.

Cowan, L. W. (1953), "A radio climatological survey of the United States," Proc. Conf. Radio Meteor, U. of Texas, Austin.

Crain, C. M., J. R. Gerhardt, and, C. E. Williams (1954), "A preliminary survey of tropospheric refractive index measurements for U. S. interior and coastal regions," IRE Trans. AP-1, 15-22.

Day, J. P., and L. G. Trolese (1950), "Propagation of short waves over desert terrain," Proc. IRE. 38, No. 2, 165-175.

Dingle, A. N. (1960), "The micro-structure of rain in a summer shower," Proc. 8th Weather Radar Conference, 99-106.

Dennis, A. S. (1961), "Performance of tropospheric scatter systems as a function of weather conditions" SRI Report No. 5, Stanford Research Institute.

Doherty, L. H., and S. A. Stone (1960), "Forward scatter from rain," IRE Trans. AP-8, No. 4, 414-418.

Doherty, L. H. (1964), "Airmass effects on tropospheric radio scatter," Can. J. Phys., 608-615.

Doherty, L. H., and G. Neal (1959), "A 215 mile 2720 Mc radio link," IRE Trans. AP-7, No. 2, 117-126.

Dougherty, H. T., and R. E. Wilkerson (1967), "Determination of antenna height for protection against microwave diffraction fading," Radio Sci. 2 (New Series), No. 2, 161-165.

Durst, C. S. (1946), "Meteorological factors in radio propagation," Physical Society of London, 193-212.

Fengler, G. (1964), "Dependence of 500 Mc/s field strength values and fading frequencies on meteorological parameters," Proc 11th Weather Radar Conference, 84-87.

Flavell, R. G. (1964), "Further radio-meteorological analysis using potential refractive index," J. Atmosph. Terr. Phys., 26, 41-49.

Flock, W. L., R. C. Mackey, and W. D. Hershberger (1960), "Propagation at 36500 Mc in the Los Angeles, California, basin," IRE Trans. AP-8, No. 3, 235-241.

Friend, A. W. (1945), "A summary and interpretation of ultra-high frequency wave propagation data collected by the late Ross A. Hull," Proc IRE, 33, No. 6, 358-373.

Fukushima, M., H. Iriye, and K. Akita (1962), Spatial distribution characteristics of atmospheric refractive index from heliocopter and kytoon observations," Jour. Radio Research Laboratory (Japan) 9, No. 45, 369-383.

Gough, M. W. (1955), "Some features of VHF tropospheric propagation," Proc IEE. Part B, 102, 43-58.

Gough, M. W. (1962), "Propagation influences in microwave link operation," British IRE, 24, 53-72.

Hay, D. R., and G. E. Poaps (1959a), "Prolonged signal fade-out on a short microwave path," Can. J. Phys., 37, 313-321.

Hay, D. R., and G. E. Poaps (1959b), "Frontal perturbation of a tropospheric scatter path," Can. J. Phys., 37, 1272-1282.

Head, H. T. (1960), "Influence of trees on T.V. field strengths at ultrahigh frequencies," Proc. IRE, 48, No. 6, 1016-1020.

Hirao, K., Y. Uesugi, and K. Tao (1952), "Propagation characteristics of VHF over a distance of 125 km," J. Geomag. Geoelect., 4, 131-140.

Holden, D. B., E. E. Gossard, and R. U. F. Hopkins (1960), "Radio meteorology and climatology of the eastern North Pacific," Research Report 966, NEL, San Diego, California.

Ikegami, F. (1959), "Influence of an atmospheric duct on microwave fading," IRE Trans. AP-7, No. 3, 252-257.

Ikegami, F. (1964), "Radiometeorological effects in propagation over the sea and islands," Review of the Electrical Communications Laboratory, (Tokyo), 12, No. 5-6, 312-324.

Ikegami, F., H. Haga, T. Fukuda, and H. Yoshida (1966), "Experimental studies on atmospheric ducts and microwave fading," Review of the Elect. Communications Laboratory, 14, No. 7-8, 505-533.

Jenkinson, G. F. (1966), "The dependence of tropospheric radio propagation on the weather and a study of radio meteorological correlations over Bass Strait," Research Laboratory Report No. 6121, Commonwealth of Australia Post-Master General's Department.

Jeske, H. (1964), "Transhorizon transmission and height gain measurements above the sea with waves in the range of 1.8 cm to 187 cm under special consideration of meteorological influences," Proc. 11th Weather Radar Conference, 458-463.

Joy, W. R. R. (1958), "Radio propagation far beyond the horizon at about 3.2 cm wavelength," Proc. IEE (Br.), 105, Pt. B, Supp. 8, 158-164. (See pp 153-157.)

Kalinin, A. I., V. N. Troitskiy, and A. A. Shur (1964), "Statistical properties of the signal in long-range USW propagation," Telecommunications, Part 1, 18, No. 7, 1-10.

Katzin, M., H. Pezzner, B. Y.-C. Koo, J. V. Larson, and J. C. Katzin (1960), "The trade-wind inversion as a transoceanic duct," J. Res. NBS 64D (Radio Prop.), No. 3, 247-253.

Kerr, R. E. Jr., J. R. Thompson, and R. D. Elliott (1962), "Quantitative assessment of the performance characteristics of the airways terminal forecasting system," Aerometric Research Inc. USWB Contract Cwb 1077.

Kiely, D. G., and W. R. Carter (1952), "An experimental study of fading in propagation at 3-cm wavelength over a sea path," Proc. IEE (Br.), Pt. 3, 99, 53-60.

Kitchen, F. A., E. G. Richards, and I. J. Richmond (1958), "Some investigations of metre-wave propagation in the transhorizon region," Proc. IEE, (Br.), Pt. B, Supp. 8, 105, 106-116.

Landsberg, H. (1960), "Physical Climatology", (Gray Printing Co., Dubois, Pa.), 200.

Lane, J. A. (1965), "Some investigations of the structure of elevated layers in the troposphere," J. Atmosph. Terr. Phys., 27, 969-978.

Lane, J. A., and P. W. Sollum (1965), "VHF transmission over distances of 140 and 300 km," Proc. IEE (Br.), 112, No. 2, 254-258.

Medhurst, R. G. (1965), "Rainfall attenuation of centimetre waves: Comparison of theory and measurement," IEEE Trans. AP -13, No. 4, 550-564.

Moreland, W. B. (1965), "Estimating meteorological effects on radar propagation," Air Weather Service Technical Report No. 183, 1, 45, 143.

Peterson, C. F., J. E. Farrow, F. M. Capps, and C. A. Samson (1966), "Propagation at 5 GHz in Europe - A comparison of predictions and measurements for various types of paths," ESSA Tech. Report IER 2-ITSA 2, U. S. Dept. of Commerce.

Pickard, G. W., and H. T. Stetson (1947), "A study of tropospheric reception at 42.8 Mc and meteorological conditions," Proc. IRE, 35, 1445-1450.

Raghavan, S., and K. Soundararajan (1962), " A study of abnormal radar propagation around Madras," Indian Jour. of Meteorology and Geophysics, 13, 501-509.

Rice, P. L., A. G. Longley, K. A. Norton, and A. P. Barsis (1966), "Transmission loss predictions for tropospheric communication circuits," NBS Tech Note 101, II , (Revised).

Rider, G. C. (1958), "Some tropospheric scatter propagation measurements and tests of aerial siting conditions at 858 Mc/s," IEE Proc. Pt B, Supp. 8, 143-152.

Ringwalt, D. L., W. S. Ament, and F. C. MacDonald (1958), "Measurements of 1250-Mc scatter propagation as function of meteorology," IRE Trans. AP-6, No. 2, 208-209.

Ringwalt, D. L., and F. C. MacDonald (1961), "Elevated duct propagation in the trade winds," IRE Trans AP-9, No. 9, 377-383.

Ryde, J. W., and D. Ryde (1945), "Attenuation of centimetre and millimetre waves by rain, hail, fogs, and clouds," Report 8670, General Electric Company Research Labs., Wembley, England.

Sabin, R. C. (1966), "A study of the meteorological conditions surrounding communications outages on the Ringstead/Gorramendi troposcatter radio link," Tech. Study-28th Weather Sqdn. (MAC), USAF.

Saxton, J. A., and H. G. Hopkins (1951), "Some adverse influences of meteorological factors on marine navigational radar, Proc. IEE, 98, III, 26-36.

Saxton, J. A., and J. A. Lane (1955), "Effects of trees and other obstacles," Wireless World, 61, 229-232.

Smith, E. K., and S. Weintraub (1953), "The constants in the equation for atmospheric refractive index at radio frequencies," Proc. IRE, 41, No. 8, 1035-1037.

Spencer, C. W. (1952), "Radio propagation at 89 Mc/s in relation to synoptic conditions," Meteorological Magazine, 81, 216.

Stark, J. W. (1965), "Simultaneous long distance tropospheric propagation measurements at 560 Mc/s and 774 Mc/s over the North Sea," Report No. K-158, Research Dept., British Broadcasting Corp.

Trevor, B. (1940), "Ultra-high frequency propagation through woods and underbrush," RCA Review, 5, 97-100.

Ugai, S. (1961), "Studies on microwave propagation within line-of-sight distance," Proc. Microwave Seminar, Tokyo, Doc. No. 6, 30-43.

Ugai, S., Y. Kaneda, and T. Amekura (1961), "Microwave propagation test in mirage district," Review of the Electrical Communications Laboratory, (Tokyo), 9, Nos. 11-12, 687-717.

Wickerts, S. (1964), "An investigation of the semi-fine structure of the refractive index field in a coastal area," Proc 11th Weather Radar Conference, 264-269.

Wiilet, H. C. (1951), "The forecast problem," The Compendium of Meteorology, (Amer. Meteor. Soc. Boston), 731-746.

12.0 Table 1. Summary of Radio-Meteorological Relationships

Weather Category	Reported By	Radio Frequency	Path Length	Location	Results	Page
Air Masses	Doherty (1964)	2720 MHz	144 km	Canada	mA = superrefractive conditions cA = low signals; no superrefractivity mP = intermediate when compared to mA and cA mT = high signals and no superrefractivity	37
	Friend (1945)	60 MHz	160 km	Mass	cP = low signals and rapid fading	36
Attenuation by Rain	Saxton and Hopkins (1951)	9375 MHz		Indian-Pacific Ocean	Attenuation of signal due to heavy rain results in a reduction of radio range.	31
	Angell et al. (1958)	3480 MHz	278 km	England	In heavy rain attenuation of the radio signal will occur with a median level fall of 15 dB.	3[illegible]
	Doherty and Stone (1960)	2720 MHz	145 km	Canada	Rain attenuation may cause an increase of fading by factor of 10.	32
Diurnal Variations	Gough (1962)	80 MHz	130 km	Arabian Gulf	Strong signal levels were observed with strong surface temperature inversions at 0600 local time. Rapid drop of 40 dB was observed at 0930 when inversion layer was dispersed by morning convection.	14
	Day and Trolese (1950)	25 MHz to 24000 MHz	43 and 74.5 km	Arizona	Nocturnal radiation produced strong radio ducts causing a diurnal change as high as 50 dB.	14
	Gough (1955)	74.47 MHz and 174 MHz	Varied	Tr[illegible]cs	West Africa land paths (Nigeria and the Gold Coast) show marked diurnal signal variations, ranging from steady daytime signals to very disturbed nocturnal signals.	15
	Ikegami (1959)	3892 MHz 4020 MHz	54.8 km	Japan	Severe nocturnal fading occurred as a result of intense diurnal variation of temperature and humidity profiles.	17
	Hay and Poaps (1959a)	2 GHz	34 km	Canada	Fadeouts more frequent at night.	18

Table 1 (Continued)

Weather Category	Reported By	Radio Frequency	Path Length	Location	Results	Page
Diurnal Variations (Cont'd)	Dennis (1961)	1262 MHz	480 km	Fla. to Bahamas	No diurnal effects.	40
	Hirao et al. (1952)	150 and 65 MHz	125 km	Japan	Frontal effect more noticeable at night.	42
	Kalinin et al. (1964)	250 to 3250 MHz	85 to 730 km	U.S.S.R.	Signals slightly lower in daytime.	39
	Flock et al. (1960)	36 GHz	18 km	Calif.	Fading range was much lower in daytime than during the night.	20
	Friend (1945)	50 MHz	160 km	Mass.	Less diurnal effect in winter.	36
	Anan'ev and Troitskiy (1964)	1 GHz	192 km	U.S.S.R.	No connection was observed between fading and time of day.	37
Ducting Gradients on RAOBs	Bean (1954)	1046 MHz	112 km	Colo.	Ducting accompanied by fadeouts over 75% of time (mountain to plains path).	46
Elevated Temperature Inversions	Crain et al. (1954)			U.S.A.	Temperature inversions of 1-3°C associated with stronger refractive layers; indicated by haze and/or cloud at boundary.	19
	Kitchen (1958)	86 and 203.5 MHz	600 km	English Channel	Elevated superrefractive layers formed by temperature inversions caused increased signal strength.	21
	Lane and Sollum (1965)	174 and 186 MHz	140 and 300 km	England	Elevated radio ducts caused by elevated temperature inversions increased radio signal strength.	21
	Jeske (1964)	160 MHz to 16.5 GHz	77.2 km	German North Sea	The influence of the low-level evaporation duct can be exceeded by subsidence-produced elevated temperature inversions.	16
	Flock et al. (1960)	36 GHz	18 km	Calif.	When the temperature inversion layer was below the height of the antenna (about 150 m) the fading range might reach 30 dB; fading ranges were small with the inversion appreciably higher than the antenna.	20

Table 1. (Continued)

Weather Category	Reported By	Radio Frequency	Path Length	Location	Results	Page
Elevated Temperature Inversions (Cont'd)	Peterson et al. (1966)	5 GHz	404 km	Europe	Serious propagation losses when elevated layers caused depression of radio beam on obstacle-diffraction path.	39
Fog and Clouds	Kiely and Carter (1952)	10,000 MHz	26 km	England	When optical visibility is limited to about 30 m, radio signals may attenuate at 0.2 dB/km.	33
	Saxton and Hopkins (1951)	9375 MHz		Polar Areas	Dense fog (low optical visibility) may attenuate radio signals significantly.	34
	Crain et al. (1954)			U.S. Pacific Coast	Strong refractive layers with stratus.	19
	Moreland (1965)			U.S. Pacific Coast	Superrefractive layers may form at top of stratus deck.	24
Forests	Head (1960)	482 MHz		Maryland	The average attenuation due to trees was about 22 dB in excess of the smooth earth value for 50 percent cover.	34
	Trevor (1940)	500 MHz		U.S.A.	12 to 19 dB attenuation/500 ft in thick woods.	34
	Baynton et al. (1965a)	7565 MHz		Columbia	Radio ducts formed beneath a canopy of trees resulted in attenuated signals and decreased signal strengths.	35
	Saxton and Lane (1955)				Attenuation in thick woods 0.02 dB/m at 30 MHz and 0.5 dB/m at 3000 MHz.	35
	Behn and Duffee (1965)			Tropics	Measured temperature inversion of 3.5°C in 16 m just above a forest canopy.	35
Land and Sea Breeze Circulation	Landsberg (1960)			U.S.A.	Sea breeze seldom extends farther inland than about 50 to 65 km.	22
	Jenkinson (1966)	1900 MHz	157 km	South Australia	Superrefraction caused by sea breeze front.	23, 9

Table 1.! (Continued)

Weather Category	Reported By	Radio Frequency	Path Length	Location	Results	Page
Monsoons	Raghavan and Soundararajan (1962)			Madras, India	Standard propagation during the monsoon (June through September); occasionally superrefractive in October; strong superrefractive conditions in March and April.	50
Precipitation	Medhurst (1965)				Attenuation of centimeter radio waves from rainfall usually greater than predicted by theory (Ryde, 1945).	29
	Anderson et al. (1947)	1.25 cm	2 km	Hawaii	Attenuation (dB/mi) was 1.5 to 2.0 times greater than the Ryde theoretical values.	30
	Saxton and Hopkins (1951)	9375 MHz		Indian and Pacific Ocean	Heavy rain results in radar range 1/3 to 1/4 of normal.	31
	Angell et al. (1958)	3480 MHz	200 km	England	In heavy rain attenuation rate .056 dB/km.	32
	Doherty and Stone (1960)	2720 MHz	145 km	Canada	Rain attenuation may cause an increase of fading by a factor of 10. Scattering from rain may at times increase signal level.	32
	Hirao et al. (1952)	150 and 65 MHz	125 km	Japan	Low signal strength on days with precipitation.	42
	Friend (1945)	60 MHz	160 km	Mass.	Periods of highest signal level accompanied atmospheric conditions that resulted in rain. For 3 to 4 hr before the start of the precipitation signal levels were high, then fading increased and the signal level dropped as the precipitation started.	36
	Anan'ev and Troitskiy (1964)	1 GHz	192 km	U.S.S.R.	Fading depth increased after a rain and decreased in settled dry weather.	37
Pressure Systems and Fronts	Joy (1958)	9375 MHz	90 to 320 km	England	Better propagation with low pressure than with high pressure systems over land paths.	44
	Joy (1956)	9375 MHz		English Channel	Signal levels were high in high pressure ridge over sea.	44
	Anastassiades et al. (1962)	2005 MHz	129 km	Greece	Northerly winds out of high pressure areas in winter gave smooth radio signals with no deep fades. In warm sectors of low pressure areas fading amplitudes were as high as 30 dB in winter and spring or when inversions developed. A cold front generally increased fading.	45

Table 1. (Continued)

Weather Category	Reported By	Radio Frequency	Path Length	Location	Results	Page
Pressure Systems and Fronts Cont'd	Arvola (1957)			U.S.A.	Brief periods of high radio signals noticed with passage of squall lines.	40
	Stark (1965)	560 GHz 774 MHz	194 km 950 km	England (North Sea)	Slow-fading generally associated with high field strength, and occurred during periods of high atmospheric pressure. Fast-fading occurred with low-level field strengths and low atmospheric pressure.	45
	Arvola (1957)			U.S.A.	Polar highs have few strong refractive gradients. Warm highs may produce a pronounced elevated superrefractive gradient.	40
	Crain et al. (1954)			Ohio	Strong refractive layers at front between mT and cP air masses.	19
	Dennis (1961)	1262 MHz	480 km	Bahamas	A drop of 15 dB in 3 hr was noted after a cold front passage.	40
	Sabin (1966)	900 MHz	800 km	England-Spain	Propagation improved with cold front passage. Most outages occurred with highly refractive layers 950-700 mb; subsidence important factor.	49
	Ugai (1961)			Japan	Fadings were infrequent during periods of inclement weather or during cold frontal passages. Strong fadings occurred in the high pressure that followed the frontal passages. Surface temperature inversions occurred mostly at night.	41
	Kalinin et al. (1964)	250 to 3250 MHz	159 to 730 km, 85 to 303 km	U.S.S.R.	10 to 20-dB drop in signal with frontal passage; slow recovery afterward. No specific cyclone-anticyclone differences.	38
	Hirao et al. (1952)	65 and 150 MHz	125 km	Japan	Highest fields with high pressure over path; fronts cause abnormally high signals; cold front had greater effect than warm front. During winter and times of precipitation the diurnal variation in field strength was small.	42
	Ikegami et al. (1966)	3980 and 4020 MHz	55 km	Japan	Marked fading occurring on two consecutive nights disappeared after a cold front crossed the path.	25
	Spencer (1952)	89 MHz	257 km	England	High field strengths twice as likely with high pressure systems as with low pressure. Extended radio ranges were observed with high pressure.	42
	Flavell (1964)			Europe	The greatest change in refractivity associated with the boundary layer in the Northwest of Europe takes place on the western side of high pressure cells.	43

Table 1. (Continued)

Weather Category	Reported By	Radio Frequency	Path Length	Location	Results	Page
Pressure Systems and Fronts Cont'd	Doherty and Neal (1959)	2720 MHz	315 km	Canada	Cold front passage caused disturbed signal with deeper fading.	46
	Hay and Poaps (1959a)	2000 MHz	34 km	Canada	Most fadeouts near center of high pressure.	44
	Hay and Poaps (1959b)	500 MHz	137 km	Canada	When the boundary of the frontal zone was about 900 m above the center of the path the fading appeared to reach a maximum. Cold fronts have greater effect than warm fronts. High fading rate within 12 hr of low center on path.	46
	Pickard and Stetson (1947)	42.8 MHz	270 km	Mass.	All types of frontal passages lowered signal levels; the amount of signal depression varied with the angle made by the front with the path.	48
Seasonal Correlations	Kalinin et al. (1964)	250 to 3250 MHz	159 to 730 km; 85 to 303 km	U.S.S.R.	Attenuation greater in summer than in winter. Signal increased and depth of fading decreased during stable conditions. Poor correlation with dielectric constant of air.	38
	Head (1960)	482 to 488 MHz		Maryland	Change of foliage with seasons caused change in attenuation.	34
	Jenkinson (1966)	1900 MHz	157 km	South Australia	Considerably less fading in the winter than in the summer.	9
	Bean (1959)			Northern Hemisphere	Maximum occurrence of ground-based ducts for the arctic in the winter. Maximum occurrence of ground-based ducts for the tropics in the summer.	12
	Gough (1962)	80 MHz	130 km	Arabian Gulf	Mean diurnal differences in signal strength in September about 40 dB. Mean diurnal differences in signal strength in January very small.	13
	Ugai et al. (1961)	1500 MHz to 11000 MHz		Japan	Moderate fadings occurred in August. Greatest fading range and frequency of occurrence was in May, and the usual diurnal trend was not present.	14
	Gough (1955)	77.47 MHz 174 MHz		Israel Cyprus	Appreciable downward trend in signal level in autumn.	15

Table 1. (Continued)

Weather Category	Reported By	Radio Frequency	Path Length	Location	Results	Page
Seasonal Correlations Cont'd	Baynton et al. (1965b)			California	Inversions were most frequent in winter instead of summer as in most areas.	16
	Hay and Poaps (1959a)	2 GHz	34 km	Canada	Fadeouts occurred more frequently in summer than in winter.	18
	Raghavan and Soundararajan (1962)			Madras, India	Standard propagation conditions are observed in June through September. Strong superrefractive gradients are very common in March and April.	50
	Friend (1945)	60 MHz	160 km	Mass.	Nighttime signals were much higher in summer than winter.	36
	Dennis (1961)	1262 MHz	480 km	Florida to Bahama Islands	Signal levels were higher in summer than in winter.	40
	Chisholm el al. (1962)	400 MHz	150 to 1330 km	U.S.A.	Median signal levels highest in summer; the seasonal differences observed were greater for the 300-km path than the 990-km path.	39
	Hirao et al. (1952)	150 and 65 MHz	125 km	Japan	Higher field strength in summer than winter.	42
Surface Temperature Inversions and Ducts	Gough (1955)	77.47 MHz 174 MHz	varied	Tropics	Surface ducts result in varying degrees of fading. Radio transmissions over land are subject to less fading than those over water unless the land paths are influenced by pronounced radiational cooling.	15
	Hay and Poaps (1959a)	2000 MHz	34 km	Canada	Fadeout accompanied a shallow transition layer in air vapor pressure through a layer thickness of about 30 m near the height of the antenna (60 m).	18
	Ikegami (1959)	3892 MHz 4020 MHz	54.8 km	Japan	Severe fading occurs at night due to strong nocturnal radiation.	17
	Ugai (1961)	1500 MHz to 11000 MHz		Japan	Surface inversions occurred mostly at night; ducts very common May through August and when mirages occurred.	41
	Day and Trolese (1950)	25 MHz to 24000 MHz	43 km 74.5 km	Arizona	In winter nocturnal cooling produced surface radio ducts that had an appreciable effect on microwave propagation.	14

Table 1. (Continued)

Weather Category	Reported By	Radio Frequency	Path Length	Location	Results	Page
Surface Temperature Inversions and Ducts Cont'd	Gough (1962)	80 MHz	130 km	Arabian Gulf	Surface ducts resulted in greatly increased radio ranges.	13
	Jeske (1964)	600 MHz to 7 GHz	77.2 km 61.7 km	German Sea	The propagation properties of these frequencies were largely determined by persistent low-level evaporation ducts	16
	Baynton et al. (1965b)			California	Radiation inversions were most frequent in the winter.	16
Thunder-storms	Coons (1947)			U.S.A.	Abnormal moisture lapse rate may form near the surface and cause radio ducts. The radio signal may be attenuated by heavy rain near the center of the storm.	24
Trade Wind Regions	Ringwalt et al. (1958)			Off-shore Florida	A strong superrefractive gradient was found at about 1500 m off the Florida coast.	51
	Katzin et al. (1960)	200 MHz		Brazil and Ascension Island	An elevated duct was present most of the time; base height 1300 to 1800 m; greatest radio ranges with both transmitter and receiver in duct.	51
	Ringwalt and MacDonald (1961)			Brazil and Ascension Island	Best month for extended range is November; base of duct 1800 m.	51
	Holden et al. (1960)			Eastern North Pacific Ocean	The most important radio-weather feature was the presence, or absence, of the elevated subsidence inversion (trade wind inversion) from spring to autumn; little ducting in winter.	52

Table 1.(Continued)

Weather Category	Reported By	Radio Frequency	Path Length	Location	Results	Page
Winds	Fengler (1964)	500 MHz	202 km	North Germany	Light surface winds were necessary for stratification of the lower atmosphere. No high radio signals during periods of high winds; both high and low signals during periods of light winds. Winds normal to the path have the greatest effect.	26
	Doherty and Neal (1959)	2720 MHz	346 km	Canada	A correlation coefficient near 1 exists between surface winds and the fading rate when a time advance of about 2 hr is applied to the fading rate record.	27
	Doherty and Stone (1960)	2720 MHz	145 km	Canada	Passage of rain and high wind through the common volume caused a high fading rate.	27
	Bauer (1961)	915 MHz	645 km	New York	A good correlation exists between wind shear and fading rate.	27
	Anderson and Gossard (1953)	10000 and 3334 MHz	90 km	England	In summer, with lower wind speeds, there is greater difference between land and sea weather data than in winter (on coasts). The correlation between 3334-MHz field strength and the wind speed is good, especially above 7 m/sec.	28
	Pickard and Stetson (1947)	42.8 MHz	270 km	Mass.	The highest fields occurred with lowest wind velocities.	28

13.0 Definitions

Advection	The process of transport of an atmospheric property solely by mass motion (velocity field) of the atmosphere; also the rate of change of the value of the advected property at a given point. Advection describes the predominantly horizontal, large-scale motions of the atmosphere.
Air Mass	An air mass is often defined as a widespread body of air that is approximately homogeneous in its horizontal extent, particularly with reference to temperature and moisture distribution; in addition, the vertical temperature and moisture variations are approximately the same over its horizontal extent.
Anomalous Propagation	The propagation of energy when it arrives at a destination via a path significantly different from the normally expected path. In radio and radar studies, it refers to the abnormal refraction of a beam of radio energy, usually applied to the superrefractive propagation rather than to subrefractive propagation.
Anticyclone (ic)	An atmospheric anticyclonic circulation, a closed circulation with respect to the relative direction of its rotation, it is the opposite of a cyclone. Because anticyclonic circulation and relatively high atmospheric pressure usually coexist, the terms anticyclone and high are used interchangeably in common practice.
Arctic Air	A type of air with characteristics developed mostly in winter over arctic surfaces of ice and snow. Arctic air is cold aloft and extends to great heights. For two or three months in the summer, arctic air masses are shallow and rapidly lose their characteristics as they move southward.

Attenuation	In physics, any process in which the flux density (or power, amplitude, intensity, illuminance etc.,) of a "parallel beam" of energy decreases with increasing distance from the energy source. Attenuation is always due to the action of the transmitting medium itself (mainly by absorption and scattering).
Cold High	At a given level in the atmosphere, any high that is generally characterized by colder air near its center than around its periphery.
Continental Air	A type of air with characteristics developed over a large land area and which, therefore, has a basic continental characteristic of relatively low moisture content.
Convection	In general, mass motions within a fluid resulting in transport and mixing of the properties of that fluid. Convection, along with conduction and radiation, is a principal means of energy transfer. As specialized in meteorology, atmospheric motions that are predominantly vertical, resulting in vertical transport and mixing of atmospheric properties; distinguished from advection.
Cumulus (cloud)	A principal cloud type in the form of individual, detached elements that are generally dense and possess sharp nonfibrous outlines. These elements develop vertically, appearing as rising mounds, domes, or towers.
Cumulonumbus (cloud)	A principal cloud type, exceptionally dense and vertically developed, occurring either as isolated clouds or as a line or wall of clouds with separated upper portions. These clouds appear as huge towers or "thunderheads." Its precipitation is often heavy and always of a showery nature. The usual occurrence of lightning and thunder within or from the cloud leads to the popular name-thundercloud.

Correlation Coefficient	Measurement of the linear association between two variables.
Cyclone (ic)	Having a sense of rotation about the local vertical the same as that of the earth's rotation: that is, as viewed from above, counter-clockwise in the Northern Hemisphere, clockwise in the Southern Hemisphere, undefined at the equator. Because cyclonic circulation and relatively low pressure usually co-exist, in common practice the terms cyclone and low are used interchangeably.
Fog	A hydrometeor consisting of a visible aggregate of minute water droplets suspended in the atmosphere near the earth's surface.
Gradient	The space rate of decrease of a function.
High Pressure System	Referring to a maximum of atmospheric pressure in two dimensions on the synoptic surface chart. Since a high on the synoptic chart is always associated with anticyclonic circulation, the term is used interchangeably with anticylone.
Inversion	In meteorology, a departure from the usual decrease or increase with altitude of the value of an atmospheric property; also, the layer through which this departure occurs (the "inversion layer"). The term generally means a temperature inversion although others are defined.
Isobar	A line of equal or constant pressure; an isopleth of pressure. In meteorology, it most often refers to a line drawn through all points of equal atmospheric pressure along a given reference surface.

Land and Sea Breeze	The complete cycle of diurnal local winds occurring on sea coasts due to the differences in surface temperature of the land and sea. The land breeze component of the system blows from land to sea and the sea breeze blows from sea to land.
Lapse (rate)	The decrease of an atmospheric variable with height; the variable generally being temperature, unless otherwise specified.
Low Pressure System	Referring to a minimum of atmospheric pressure in two dimensions on a surface synoptic chart. Since a low on a synoptic chart is always associated with cyclonic circulation, the term is used interchangeably with cyclone.
Maritime Air	A type of air with characteristics developed over an extensive water surface which, therefore, has the basic maritime quality of high moisture content in at least its lower levels.
Meso-scale	The study of meteorological processes larger than the micrometeorological processes, but smaller than the cyclonic scale. For example, the weather beyond range of normal observation, but between weather stations; something that could be undetected by two stations, such as tornadoes and thunderstorms. Also included in this scale are local effects, such as influence of topographic features.
Micro-scale	The study of the smallest scale features of weather is micrometeorology; e.g., boundary layer phenomena such as temperature changes from the surface to a few feet above the surface over a small field, etc.
Mirage	A refraction phenomenon wherein an image of some object is made to appear displaced from its true position. The abnormal refraction responsible for mirages is invariably associated with abnormal temperature distributions that yield abnormal spatial variations in the refractive index.

Monsoons	A name for seasonal winds, first applied to winds over the Arabian Sea, but later extended to similar winds in other parts of the world. The primary cause is the much greater annual variation of temperature over large land areas compared with neighboring ocean surfaces, causing an excess of pressure over the continents in winter and deficit in summer, but other factors such as the relief features of the land have a considerable effect.
Polar Air	A type of air with characteristics developed over high latitudes, especially within the subpolar highs. Continental polar air (cP) has a low surface temperature, low moisture content, and especially in its source regions, has great stability. It is shallow in comparison with arctic air. Maritime polar air (mP) is initially similar to continental air, but in passing over warmer water it becomes unstable with a higher moisture content.
Radiational Cooling	In meteorology, the cooling of the earth's surface and adjacent air, accomplished (mainly at night) whenever the earth's surface suffers a net loss of heat due to terrestrial radiation.
Radiosonde	A balloon-borne instrument for the simultaneous measurement and radio transmission of meteorological data; primarily on pressure, temperature, and humidity in the vertical scale.
Rain Forest	Generally, a forest which grows in a region of heavy annual rainfall. In tropical rainforests trees may be 150 ft tall and grow so close together that the crowns form a dense canopy that prevents much of the sunlight from penetrating to the ground.
Refractometer	An instrument for measuring the index of refraction of a liquid, gas, or solid. Refractometers in general use in meteorology operate in the microwave region and are based on the principle that the resonant frequency of a cavity depends on the dielectric constant of its contents.

Squall Line	Any line or narrow band of active thunderstorms; a mature instability line.
Standard Propagation Conditions	The propagation of radio energy over a smooth spherical earth of uniform dielectric constant and conductivity under conditions of standard refraction in the atmosphere, that is, an atmosphere in which the index of refraction decreases uniformly with height at a rate of 12-N-units/1000 ft or about 40 N-units/1000 m.
Subrefractive Conditions	Refraction by an atmosphere or section of the atmosphere in which there is a positive gradient of refractive index with height.
Subsidence	A descending motion of air in the atmosphere, usually with the implication that the condition extends over a rather broad area.
Superrefractive Conditions	Refraction by an atmosphere or section of the atmosphere in which the index of refraction decreases with height at approximately twice the normal rate.
Synoptic Situation	The general state of the atmosphere as described by the major features of synoptic charts; the existing weather conditions over a wide area at a particular time as visualized on an analyzed weather map.
Synoptic Climatology	The study and analysis of climate in terms of synoptic weather information, principally in the form of synoptic charts.
Thunderstorm	In general, a local storm produced by cumulonimbus clouds, and always accompanied by lightning and thunder, usually with strong gusts of wind, heavy rain, and sometimes hail. It is usually of short duration, seldom over 2 hr for any one storm.

Trade Winds — The wind system, occupying most of the tropics, which blows from the subtropical highs toward the equatorial trough; a major component of the general circulation of the atmosphere.

Tropical Air — A type of air with characteristics developed over low latitudes. Maritime tropical air (mT), the principal type, is produced over the tropical and sub-tropical seas. It is very warm and humid, and is frequently carried poleward by the circulation of the subtropical highs.

Turbulence — A state of fluid flow in which the instantaneous velocities exhibit irregular and apparently random fluctuations so that in practice only statistical properties can be recognized and subjected to analysis.

Warm High — At a given level in the atmosphere, any high that is warmer at its center than at its periphery.